REPORT NO. GDC-SP-83-052
CONTRACT NO. NAS 8-35039

DEFINITION OF TECHNOLOGY DEVELOPMENT MISSIONS FOR EARLY SPACE STATION

ORBIT TRANSFER VEHICLE SERVICING

VOLUME 2 — TECHNICAL REPORT

June 1983

GENERAL DYNAMICS
Convair Division

VOLUME 1   EXECUTIVE SUMMARY

VOLUME 2   TECHNICAL REPORT

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30 June 1983

Prepared By
GENERAL DYNAMICS CONVAIR DIVISION
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FOREWORD

This study report was prepared by General Dynamics Convair Division (GDC) for the National Aeronautics and Space Administration Marshall Space Flight Center (NASA/MSFC) in accordance with Contract NAS8-35039, Data Requirement Number DR-4. The results were developed from October 1982 to June 1983. Final documentation is provided in two volumes:

Volume 1	Executive Summary
Volume 2	Study Results

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ACRONYMS

ACS	Attitude Control System
AEU	Aft Electrical Unit
ATP	Authority to Proceed
CCW	Counter Clockwise
CDR	Critical Design Review
CG	Center of Gravity
C&W	Caution and Warning
DDT&E	Design, Development, Test and Evaluation
EMU	Extra-vehicular Maneuvering Unit
ET	External Tank
EVA	Extra-vehicular Activity
GDC	General Dynamics Convair Division
GEO	Geostationary Earth Orbit
GH_2	Gaseous Hydrogen
IMS	Integration Management System
I/O	Input/Output
IOC	Initial Operating Capability
I_{sp}	Specific Impulse
IVA	Intra-vehicular Activity
LEO	Low Earth Orbit
LeRC	Lewis Research Center
LH_2	Liquid Hydrogen
LRU	Line Replaceable Unit
LO_2	Liquid Oxygen
MLI	Multi-Layer Insulation
MM	Manned Mission Module
MSFC	Marshall Space Flight Center, NASA
OTV	Orbital Transfer Vehicle
PDR	Preliminary Design Review
P/L	Payload
RCA	Remote Controlled Arm
RF	Radio Frequency
RMS	Remote Manipulator System
R/R	Remove/Replace
RU	Replacement Unit
S/C	Spacecraft
SS	Space Station
STS	Space Transportation System
TBD	To be Determined
TDM	Technology Development Mission
TMS	Teleoperator Maneuvering System
TV	Television

1. INTRODUCTION

Currently, all upper stages and/or orbital transfer stages are of the expendable type. With the operational capability of the Space Shuttle, this mode of operation will change and these stages will become reusable. With the coming of the manned space station, the OTV will evolve further to a more capable, higher technology system. Studies have shown that a change from ground-based to space-based OTVs offers improved operational economy, better vehicle performance, freedom from the constraints of Orbiter payload bay dimensions, and freedom from the constraints of ground operation schedules.

A space-based OTV requires that servicing be performed in orbit to accomplish turnaround of the vehicle for subsequent flights. This servicing would most likely be performed at a Space Station. This study effort addressed both the OTV and the Space Station by identifying and defining the servicing capability requirements. The term "servicing" is used in a broad sense, encompassing not only direct servicing operations such as refueling, repair, and checkout, but also related support activities such as payload/OTV integration, docking/berthing/handling, logistics/storage, and prelaunch/postlaunch processing.

The study (1) defined the testbed role of an early (1990) manned Space Station in the context of a space-based OTV evolutionary development and flight demonstration technology plan which would result in an OTV servicing operational capability by the mid 1990's, and (2) conceptually defined a set of OTV servicing technology development missions (TDM) to be performed on an early Space Station.

Our study was based on systematic examination of end-to-end operations postulated for an OTV engaged in routine missions to and from the Space Station. In a sense, we generated a top level definition of a capability similar to that of launch centers on the ground. We kept this parallel in mind so that our study considered all aspects of OTV servicing.

We began by identifying mission requirements for space-based OTVs, and the operational space-based OTV capabilities needed by the mid 1990s. We identified space-based OTV servicing capabilities that must be demonstrated by ground tests, Shuttle sortie tests, and early Space Station tests. This analysis enabled us to illustrate the testbed role of an early Space Station by developing the technology objectives and requirements for missions that are forerunners of actual operations in the space-based mode. Next, we generated conceptual designs of the tests proposed to be performed on the initial Space Station in the areas of propellant transfer/storage and reliquefaction, docking and berthing, maintenance, and OTV/payload integration. We performed trade studies to optimize the designs. An end-to-end mission operations analysis was performed in each of the above areas which defined the timelines, manpower, and support equipment requirements. In addition, accommodation requirements on the initial Space Station were identified. Finally, we developed the programmatics and preliminary cost estimates for accommodating the selected TDMs.

Under subcontract, Hamilton Standard assisted us in the mission definition and operations analysis tasks. Using their extensive experience in areas dealing with current EVA integration, operations, and applications, they made direct contributions to requirements, concepts, trade studies, and operations analyses.

The data contained in this report starts out with a description of the technical approach which was used in the conduct of the study in defining the technical aspects of the TDMs. Included in the technical approach is an assessment of a candidate space-based OTV. This candidate concept was used as a strawman to generate TDM concepts and operations. Then the requirements, conceptual design, and operations descriptions are presented collectively for each of the four selected TDMs, as well as a design for a combined TDM. A summary of the required initial Space Station accommodations for all TDMs follows. In the programmatics area, the development plans and schedules for the TDMs are presented along with preliminary cost estimates. In addition, a preliminary discussion of what can be done with the TDM equipment in an operational environment is presented. Finally, the conclusions of the study and the recommendations for follow-on activities are discussed.

2.0 TECHNICAL APPROACH

The objectives of this study are as follows:

1. Define the testbed role of an early (1990) manned Space Station in the context of a space-based OTV evolutionary development and flight demonstration technology plan which results in an OTV servicing operational capability by the late 1990's.

2. Identify servicing capabilities for both OTV and the Space Station

Direct Servicing	Support activities
- Refueling	- Payload/OTV integration
- Maintenance	- Propellant storage
- Checkout	- Prelaunch/post-launch processing

3. Conceptually define an OTV servicing technology development mission(s) to be performed on an early Space Station.

The following ground rules and guidelines were used in the performance of the study:

1. Maximum use will be made of results from prior and current projects and government-sponsored studies.

2. Space Shuttle will be considered as the earth launch vehicle - doesn't preclude consideration of augmented Shuttle possibilities.

3. An early Space Station will be operational in 1990.

4. Technology development missions will start in 1991.

5. IOC of space-based OTV in 1994.

6. A Teleoperator Maneuvering System (TMS) will be available to support on-orbit operations.

Figure 2-1 is a task flow and logic diagram of the overall study approach. It highlights principal tasks and their relationship to periodic reviews. The technical work was accomplished in six months, with reporting completed two months later.

We began (Task 1.0) by identifying missions suitable for space-based OTVs, and the operational space-based OTV capabilities needed by the late 1990s. We identified space-based OTV servicing capabilities that need to be demonstrated by ground tests, Shuttle sortie tests, and early Space Station tests. This analysis enabled us to illustrate the testbed role of an early Space Station by developing the technology objectives and requirements for missions that are forerunners of actual operations in the space-based mode.

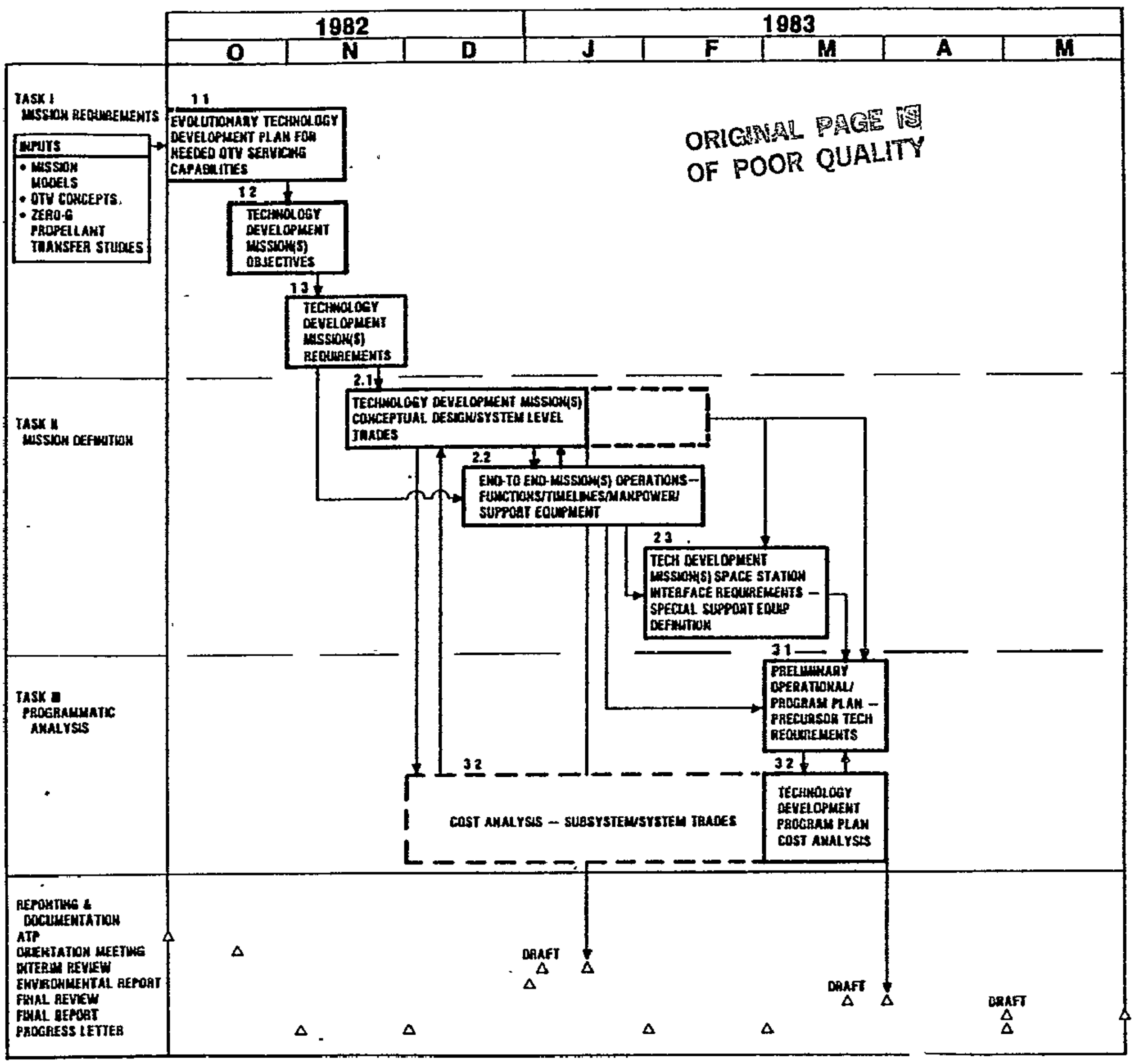

Figure 2-1 Program Task Flow

In Task 2.0 we generated conceptual designs of the tests proposed to be performed on the initial Space Station. These tests were designated Technology Development Missions (TDM). Trade-off studies were performed to optimize the designs. An end-to-end mission operations analysis was performed for each of the recommended TDMs which defined the timelines, manpower, and support equipment requirements. In addition, accommodation requirements on the initial Space Station were identified.

In Task 3.0 we developed the programmatics and preliminary cost estimates for accommodating the selected TDMs.

Under subcontract, Hamilton Standard assisted us in the mission definition and operations analysis tasks. They have extensive experience in areas dealing with EVA integration, operations, and applications, and made direct contributions to requirements, concepts, trade studies, and operations analyses. As a supplier of the Shuttle extravehicular mobility unit, Hamilton Standard is the major source of study data on the use and application of this device and ancillary equipment. Their background includes the most current space operations and satellite servicing studies.

During Task 2.1, Hamilton Standard provided inputs on EVA influences and requirements. They also provided inputs to the trade studies to ensure that the above influences and requirements have been fully recognized and evaluated.

In Task 2.2, Hamilton Standard assisted us in the end-to-end operations analysis. They defined the EVA capabilities of a crewman, man/machine interface design compatibility, and EVA procedures. They generated EVA timeline analyses identifying any areas of conflict with EMU operations, and identified Space Station IVA/EVA-related structures and support equipment requirements to provide an optimal operations transition.

This study was performed simultaneously with the "Space Station Needs, Attributes and Architectural Options" study for NASA Headquarters. That study also performed investigations related to a Space Station OTV base. We set up close cooperation between the study teams to assure maximum information flow and generated detailed task planning to assure no duplication of effort. Each study effort benefited significantly from the combined activities.

The data contained in the following subsections discusses the approach we used to accomplish Tasks 1.0 and 2.0. It also contains an assessment of a candidate space-based OTV used as a strawman to generate TDM concepts and operations. The results of Tasks 1.0 and 2.0 are presented in Sections 3.0 thru 8.0.

2.1 MISSION REQUIREMENTS

The following are the objectives of this task:

1. Develop a potential OTV mission scenario based on current data base
   - NASA
   - DoD
2. Develop a mission-derived OTV capability needs scenario
   - Mission drivers
3. Compile space-based OTV mission objectives and requirements
4. Generate evolutionary technology development testing plan
   - Ground
   - Shuttle
   - Early Space Station

4. Generate Space Station technology development mission objectives

5. Generate Space Station technology development mission requirements

2.1.1 EVOLUTIONARY TECHNOLOGY PLAN

Figure 2-2 indicates our approach to this task. We investigated potential OTV mission scenarios based on the current data base. It included appropriate NASA and DoD mission models, operations, and technology planning studies; government and contracted satellite studies; and our General Dynamics data base. It utilized specifically the Space Transportation System Nominal Mission Model (FY 1983-2000) Revision 6, October 1982 prepared by Donald Saxton, Program Development, MSFC. In our analysis we determined that the Nominal Mission Model Rev. 6 was the most comprehensive for the 1990-2000 time period and included data for all the potential users. Thus we used the data in this mission model to generate the OTV mission requirements. Figure 2-3 is a summary, from the MSFC Rev. 6 mission model of the upper stage missions envisioned for the 1990's. It is postulated that the STS Centaur will accomplish the missions shown through 1993 when a space-based OTV would be available.

Figure 2-4 shows the driving design requirements for the space-based OTV to meet the mission model. It shows the maximum delivery payload weights envisioned for a single flight. Payload lengths are not shown as they are not a design driver as they can be for a ground-based OTV. The unmanned and manned servicing mission requirements are also design drivers, especially the return payload requirements. The descriptions of these payloads and their missions can be found in the MSFC mission model.

We generated a representative space-based OTV concept which met these mission requirements in order to help understand the servicing functions to be performed, and guide the conceptual designs of the TDMs. The definition of this concept is presented in Section 2.2.

Having identified the mission requirements, we then performed an OTV mission functional/operational analysis to identify the required servicing functions to be performed on the space station.

Figure 2-5 is a functional flow diagram for space-based OTV operations which outlines the major processes and resources involved within the system. In order to maintain simplicity for presentation, communication links, navigational aids and ground support functions are not shown in the first level diagram. These functions have been considered within the context of other gross functional listings.

The payload module may be either a manned module or an unmanned servicing module. Orbit payloads will be delivered to the desired orbit or serviced on orbit, but are not returned to the space station. It is acknowledged that receive, assemble and demate processes are maintenance functions and are shown on this diagram to provide clarity of operations.

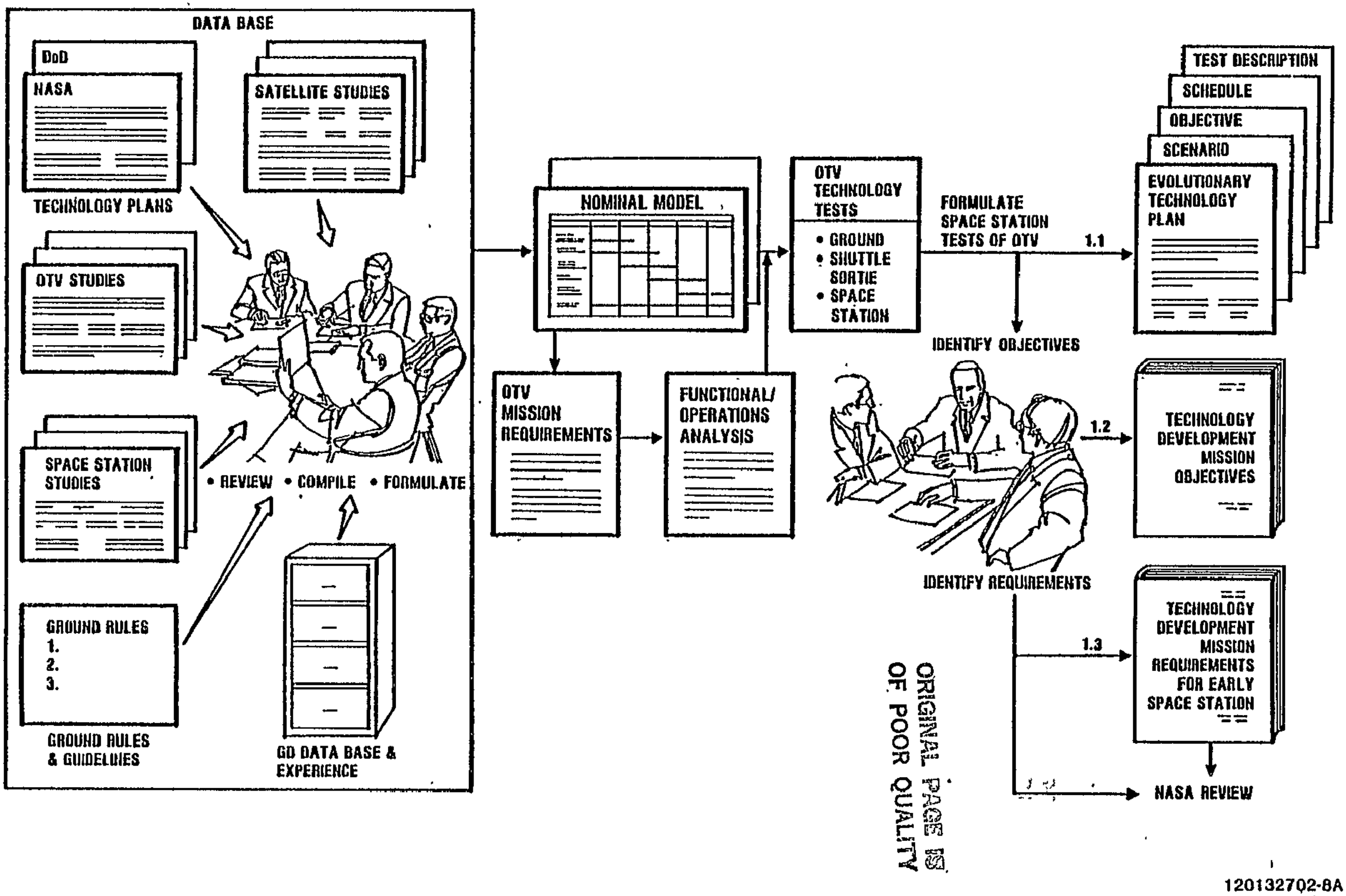

Figure 2-2 Task 1 Mission Requirements Approach

Missions	Total	Missions/FY														
		1986	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000
		← STS Centaur →								← OTV →						
Long satellites	49		1	1	2	1	1	3	1	7	6	7	8	7	1	3
Short satellites	82		3	7	6	4	5	4	7	10	5	7	6	7	4	7
Experimental GEO platforms	1				1											
Operational GEO platforms	11									2	1	2	1	2	1	2
Very large platforms	1													1		
Unmanned servicing	9						1				1	1	2	1	1	2
Manned sorties	7										1	1	1	1	1	2
Manned GEO station	2															2
Solar system exploration	16	2		2		1	1	2	1	2	1	1	1	1	1	
Totals	178	2	4	10	9	6	8	9	9	21	15	19	19	20	9	18

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Figure 2-3 Nominal High-Energy Upper Stage Mission Model, Rev. 6

	Weight (Klb)	Mission
Operational GEO platform	14.0	Deliver
Large platform	Multiple OTV flights	Deliver
Other satellites	Multiple satellites to 14.0	Deliver
GEO station element	16.0	Deliver
Unmanned servicing	6.0 up 2.0 down	Round trip to GEO
Manned sorties	13.0 up 13.0 down	Round trip to GEO
Solar system exploration	Up to 12.0	Escape

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Figure 2-4 Mission Model Payload Requirements

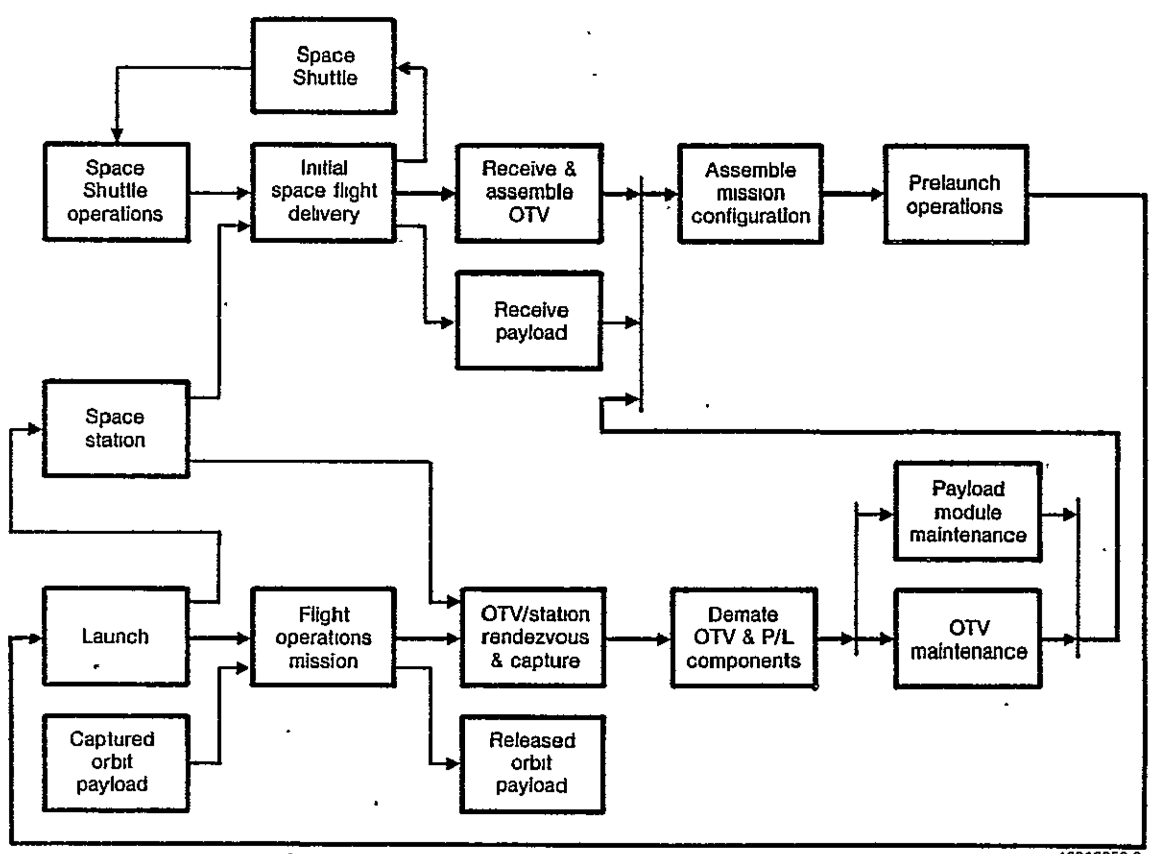


Figure 2-5 Space-Based OTV Operations

Figure 2-6 and 2-7 are second tier level functional flow diagrams showing a typical payload delivery mission, and depicting the major processes involved in a typical manned mission operating from and returning to a space station. Additional functional analysis was performed, and the flow diagrams are presented in Appendix A.

The servicing functions that were identified are called out on Figure 2-8. These functions were analyzed further in order to determine what functions should be tested in an evolutionary sequence, with emphasis on the tests to be performed on the initial space station, and what testing levels should be used in developing OTV technology.

As illustrated in the figure, we then constructed an OTV development test matrix to identify the testing level (ground, Shuttle sortie, Space Station) of the development tests. The major driver in specifying a space test is the impact of a zero-g testing time, test setup weight and volume constraints of the Orbiter (scaling effect), and the economics of using the manned Space Station.

A time-phased schedule of when the tests should be performed to meet the required mission scenario was then prepared.

The test matrix in Figure 2-8 is an example of the matrices that were developed for the functions shown. The functions shown are the ones we started with and evolved into the ones that are presented in Section 3.0 thru 6.0 for the individual TDMs.

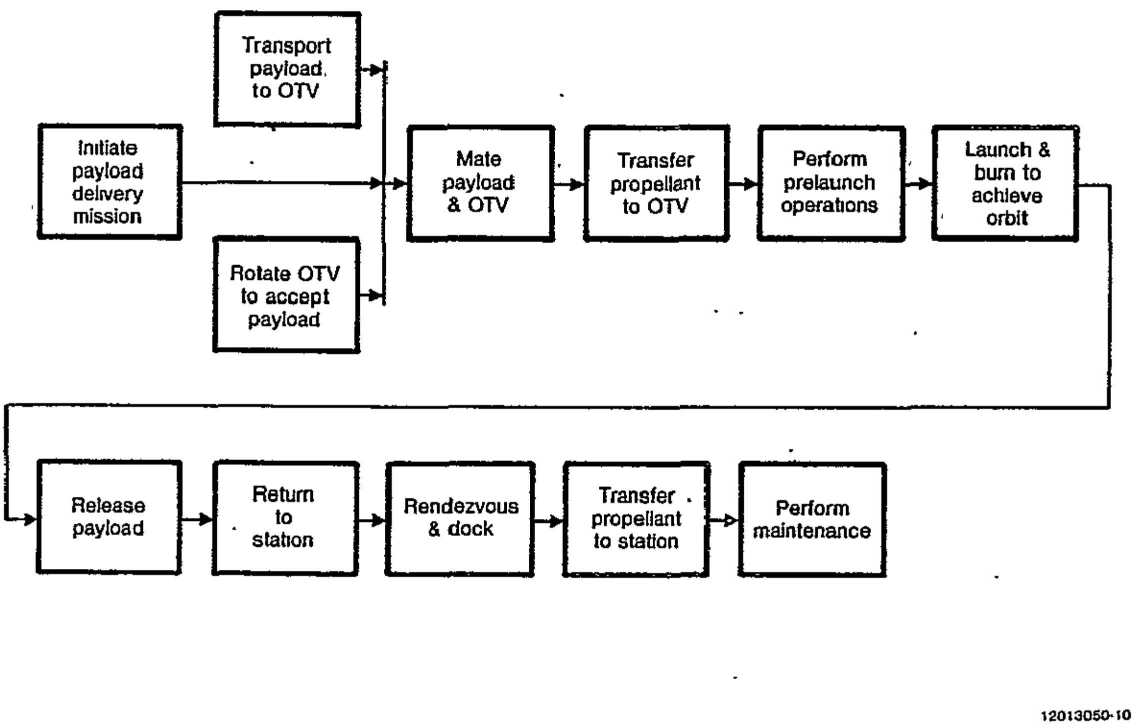


Figure 2-6 Operational Mission - Payload Delivery

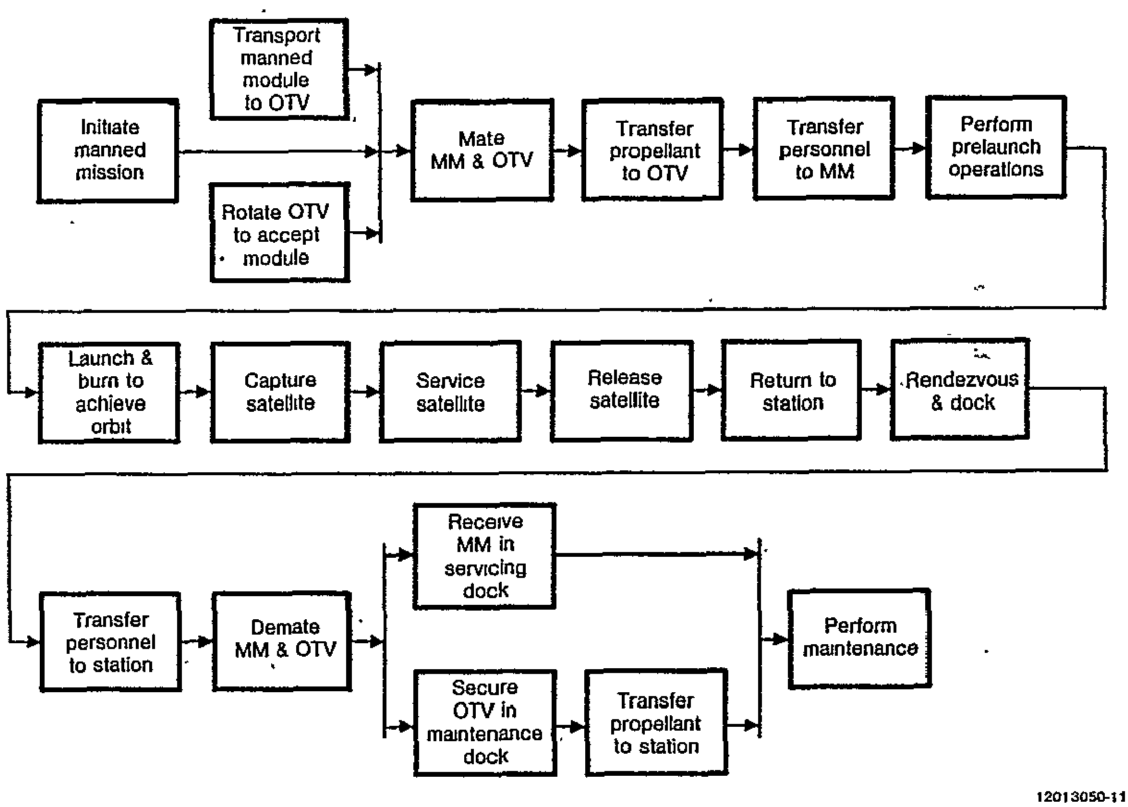


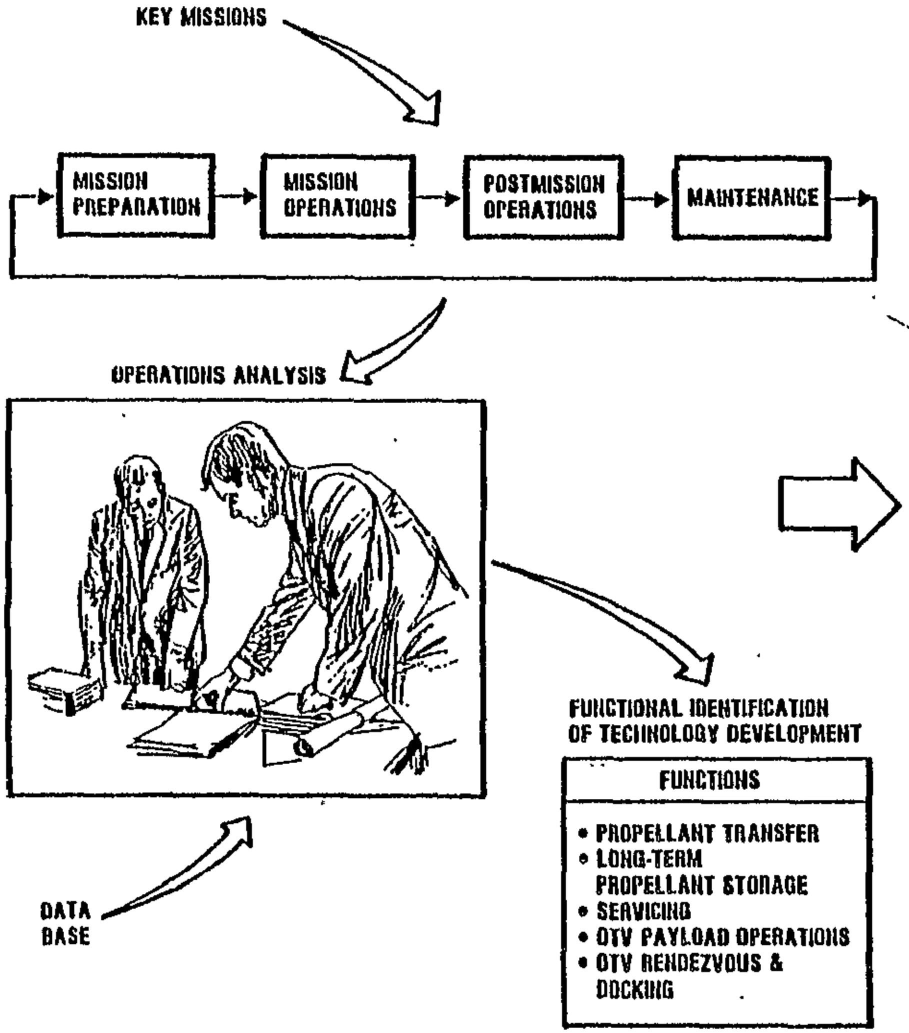
Figure 2-7 Operational Mission - Manned Module

2.1.2 TECHNOLOGY DEVELOPMENT MISSION OBJECTIVES. As indicated on Figure 2-2, the evolutionary technology development data with emphasis on the initial Space Station was inputed into this task and objectives for the TDMs were generated. These are contained in Sections 3.0 thru 6.0 for the individual TDMs.

2.1.3 TECHNOLOGY DEVELOPMENT MISSION REQUIREMENTS. As indicated on Figure 2-2, the TDM objectives were inputed into this task and requirements for the TDMs were generated. These are contained in Sections 3.0 thru 6.0 for the individual TDMs.

2.2 BASELINE SPACE-BASED OTV

In order to understand the space station servicing functions for a space-based OTV, and design TDMs to develop the technologies for these functions, we felt that we needed a baseline space-based OTV. An OTV optimized for the



SPACE-BASED OTV TECHNOLOGY DEVELOPMENT TESTS

FUNCTION	DEVELOPMENT TESTS			POTENTIAL TECHNOLOGY DEVELOPMENT BY PRECEEDING SYSTEMS
	GROUND	SHUTTLE SORTIE	SPACE STATION	
PROPELLANT TRANSFER				
- Docking fluid interface	X	X	X	
- Transfer line chilling	X	X	X	
- Receiving tank chilling	X	X	X	
- Propellant acquisition		X	X	
- Mass transfer		X	X	
- Transfer time parametrics	X	X	X	
- Mass gaging		X	X	
- Reduction of losses	X	X	X	
- Monitoring	X	X	X	
LONG TERM PROPELLANT STORAGE				
- Monitoring	X			
- Insulation	X			
- Stratification/Mixing		X	X	
- Venting	X	X	X	
- Reliquification	X		X	
SERVICING (INSPECTION/MAINTENANCE/VERIFICATION)				
- Propulsion (tankage and lines)	X		X	
- Engine	X		X	
- Avionics	X		X	
- Crew Module	X		X	
- Aerobrake	X		X	
- IVA/EVA operations & procedures	X	X	X	
- Changeout vs repair level	X		X	
- Open cherry picker operations	X		X	
- Shirt sleeve hanger operations	X		X	
OTV PAYLOAD OPERATIONS				
- Storage	X			
- Handling	X		X	RMS operations
- Checkout	X			
- Servicing	X		X	
- Removal	X		X	
OTV RENDEZVOUS AND DOCKING				
- Docking interface	X	X	X	
- Control and monitoring	X		X	Shuttle/Space Station
- Stabilization and Control	X	X	X	RMS retrieval of payloads
- Berthing operations	X	X	X	Shuttle/RMS

TECHNOLOGY DEVELOPMENT TEST OUTLINE

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Figure 2-8 OTV Technology Development Tests Matrix

space environment and on-orbit maintenance will differ greatly from its ground based counterpart, and will offer significant advantages. A wide range of OTV concepts addresses the key issues shown in Figure 2-9. Our baseline vehicle, illustrated on the upper right, served as the basis for generating the servicing requirements. A NASA Headquarters Concept with many good features is shown on the lower right.

2.2.1 OTV CONCEPT. The baseline Orbital Transfer Vehicle Concept (see Figure 2-10) is for an advanced OTV designed specifically for the space environment, and with modular philosophy to simplify logistics, maintenance and reconfiguration for different missions. Vehicle elements peculiarly adaptable to a space-based vehicle are summarized below:

- Lightweight Spherical Propellant Tanks
- Modular Tankage Arrangement for Mission Flexibility
- Fixed Aerobrake
- Lightweight Open Truss Structure
- Universal Payload Interface Module
- Quick Changeout Astrionics, ACS, Propellant Feed and Main Engine Modules
- Fixed High Area Ratio Engine Nozzles

Advantages
- Free from Shuttle constraints (size, loads)
- Reusable (lower cost)
- Modularity (mix & match capability)

Key Issues
- Long-term space exposure
- Orbital integration, servicing
- Efficiency (low weight, high Isp)
- Low-cost operations (propellant delivery to LEO)
- Deployment & retrieval
- Future payloads & mission characteristics

Technology needs
- Lightweight (thin gage) tanks
- Lightweight (composite) structure
- Lightweight/high temperature aerobrake materials
- Long life/space maintainability engine (low weight, high Isp
- Cryogenic propellant management — thermal control (MLI insulation, mixing, venting), propellant acquisition gaging
- Meteoroid & space debris protection
- Redundant, fault-tolerant, hardened avionics
- Auto rendezvous/docking

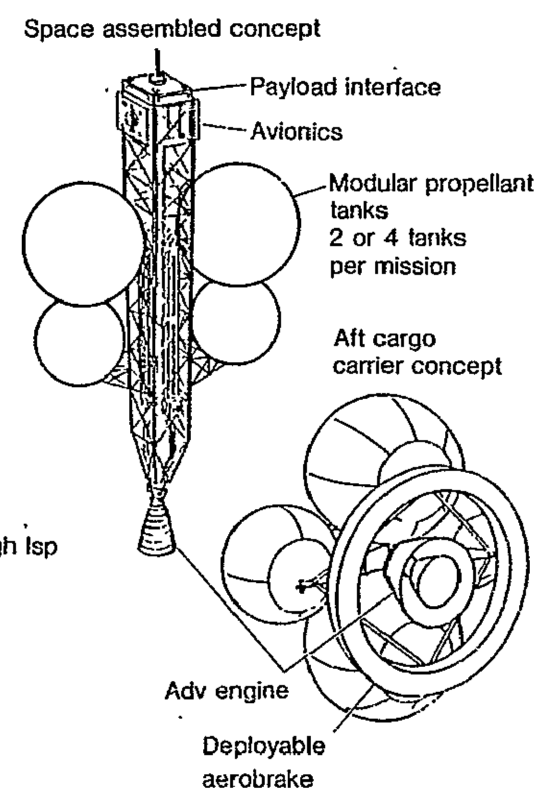

Figure 2-9 Space-Based OTV

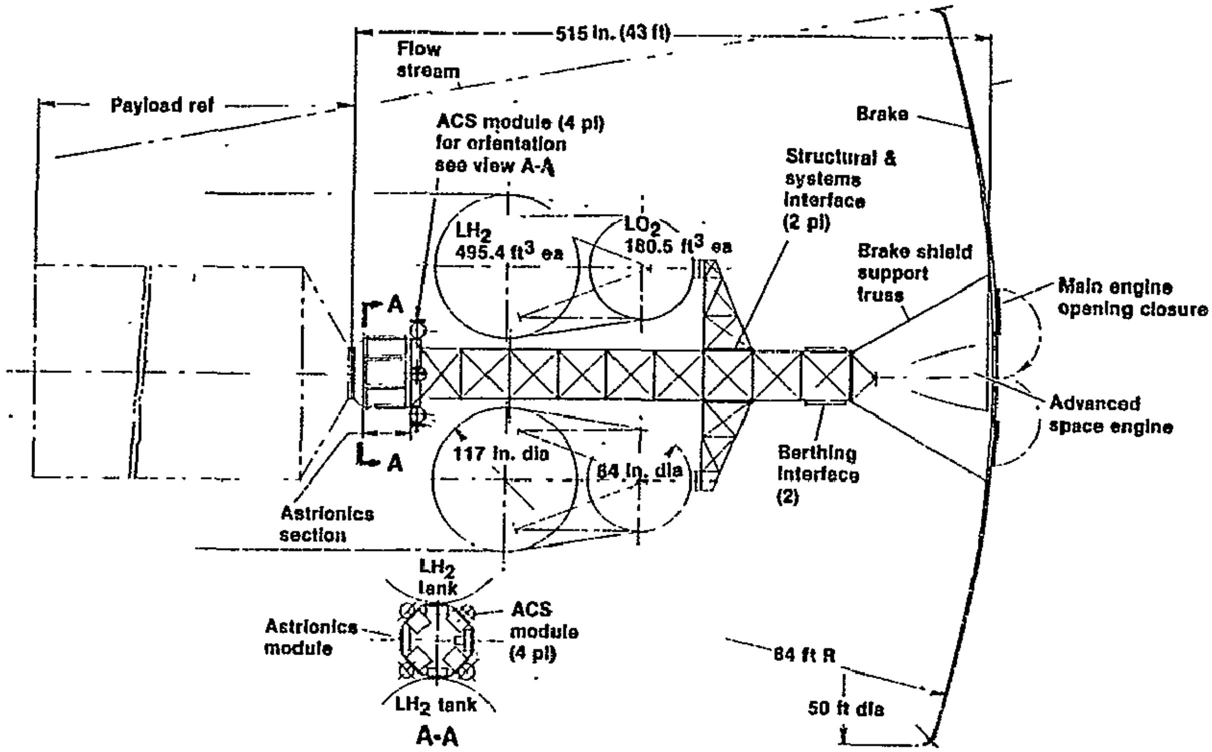

Figure 2-10 Representative Space-Based OTV Concept

The core section for this concept is a truss beam which contains subsystems such as plumbing, disconnects, astrionics, berthing interfaces, a payload interface, and attitude control thrusters. This core section is regarded as the primary portion of the vehicle with provisions to allow quick change-out of components such as the tanks, engine(s), and astrionics packages.

Referring to Figure 2-10, this concept uses four tanks attached to the core section with cantilever trusses. The trusses are fixed to the tanks and interface with the core section through a systems disconnect panel and structural attachments. These cantilever trusses provide a means for supporting and handling the tanks during transportation; during connection and disconnection from the core section; and as a holding device during storage. A typical tank attachment consists of engaging the hinge side of the cantilever truss to the core truss and rotating until the structural latches engage. A retractable disconnect panel on the core section is then actuated which engages the disconnect fittings.

The fuel tanks are supported from the oxidizer tanks with a truss system. One complete tank module is composed of an oxidizer tank, a fuel tank, an interconnecting truss and the cantilever truss which is plugged into the core section. The truss members between the tanks are equipped with drag struts at the forward ends for lateral support and disconnection from the core section; and as a holding device during storage. A retractable disconnect panel on the core section actuates to engage the disconnect fittings.

The aerobrake is supported from the core section with a conical truss structure and is equipped with two doors for covering the engine opening. An alternate procedure would delete these doors and run the engine at low idle mode during atmospheric braking.

The forward end of the core section is equipped with an octagon structure called the astrionics module which houses the astrionic packages and provides an interface for the payload. The astrionics packages can be quickly disconnected from this module for transport to a shirtsleeve Space Station module for maintenance or for return to earth.

The aft end of the core module has an interface panel for the engine package. This interface panel contains disconnects for all the engine fluid and electrical lines and also contains a structural latch system for securing the engine package to the core section. A typical engine package consists of a flat interface panel with disconnects, a thrust cone, a set of gimbal lines, and a thust vector control system. This package contains all engine systems and is designed to plug onto the core section as a single package.

Four ACS modules are located at the aft end of the astrionics module and are oriented at a 45° position as shown in view "A-A". Each of these ACS modules are complete, self-contained units consisting of a spherical tank, an acquisition system, a cluster of thrusters, electrical wiring harnesses (with a disconnect) and an interface boss for "quick" type connection to the core section. The propellant is hydrazine. Prior to installation the tanks are charged with propellant, pressurized, and locked up.

An alternate ACS system which maximizes performance and reduces the number of propellants which must be provided at the station is a two gas (or two liquid) LOX/H_2 ACS system drawing propellant from a "start basket" in the main tanks.

A third possibility under consideration is an ACS system which uses hydrogen gas. Slugs of liquid hydrogen are taken from the main tanks and injected into a hot flash tank which in turn feeds the thrusters. This alternate ACS system will require a slug pump, interconnecting plumbing and a pressure control system. The thrusters would be modularized for simple one step plug in type replacement.

Figure 2-11 illustrates the four tank module version of the OTV for missions which require more payload capability, especially for the manned mission. Two additional sets of tanks can be added to the baseline concept as shown in the figure.

Figure 2-12 details the OTV weights. Note that these weights are for a "clean sheet" all-up design which is designed exclusively for operation in space. Advanced composites for the truss structures and advanced metal forming procedures for the propellant tanks are assumed. The propellant tanks and structure are designed to support a full propellant load at vehicle accelerations of 1.2 g's or less (for maximum weight efficiency they cannot carry propellants during a Shuttle delivery flight). The propellant tankage as designed is not limited by the Orbiter volume or dimensions. If the optimistic weights assumed here are not achievable, the propellant capacity of the tankage can be increased to retain the performance capability.

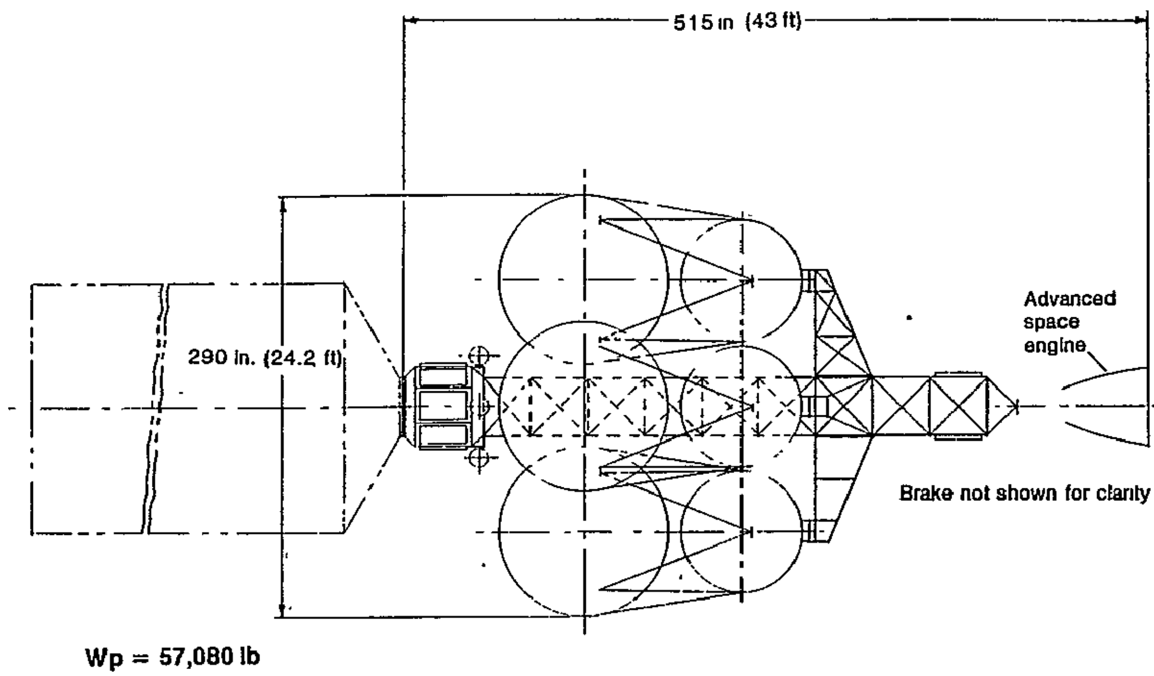

Figure 2-11 Representative Space-Based OTV Concept

A. Core assembly	
Propulsion system group	640
Flight control group	230
Fluid system group	150
Electrical group	70
Guidance & navigation	60
Communications & control	70
Docking subsystem	140
Primary structure	240
Contingency	240
Core assembly inert weight	1,840
Auxiliary propellant	60
Core assembly allup weight — all propulsive	1,900
Aerobrake	1,690
Core assembly allup weight — aerobraked	3,590

B. Tank assembly	2 tanks	4 tanks
Basic structure	400	800
Secondary structure	110	220
Insulation	100	200
Propellant, pressurization & electrical group	100	200
Contingency	110	220
Tank inert weight	820	1,640
C. Propellant (O_2/H_2 at 6:1)		
Unusable + losses	140	280
Usable	28,400	56,800
Stage at propellant depletion — all propulsive	2,860	3,820
— aerobraked	4,550	5,510
Stage at launch — all propulsive	31,260	60,620
— aerobraked	32,950	62,310
Usable propellant mass fraction — all propulsive	.909	.937
— aerobraked	.862	.912

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Figure 2-12 Preliminary Weight Summary
Potential Representative Space-Based OTV Mass Fractions

2.2.2 OTV ENGINE CHARACTERISTICS. The Advanced Space Engine integrated into this concept is specifically designed for extended operation and on-orbit maintenance as well as high performance. The weights and performance data in Table 2-1 are derived from Rocketdyne data generated in an earlier contract. (OTV Concept Definition Study - NAS8-33533)

The engine may be modified for low thrust with a ground installed kit fitted to the nozzle throat coupled with altered propellant feed system adjustments to allow it to operate for long periods in pumped idle mode. This modification allows the engine to operate at 10% nominal thrust at a slightly lower Isp ~465-470.

The man rated OTV, not illustrated, may be configured with dual main engines for redundancy. The OTV Concept Definition Study concluded, however, that safety and redundancy issues are better resolved with a separate propulsion system removed physically from the main engine. Most failure modes for the main engine will also result in the loss of a second engine located adjacent to it. An augmented ACS which is capable of generating appreciable vehicle acceleration (0.01g) with reasonable performance (Isp > 400) may fulfill abort criteria better at a lower overall weight than a dual engine arrangement.

Backup rescue vehicle operations/benefits have not been assessed in the context of an operational manned space-based OTV as an alternative to main propulsion redundancy.

Table 2-1 Advanced Space Engine Characteristics

		Advanced Space Engine - Baseline -
Thrust	(lb_F)	10,000
Chamber Pressure	(Psi)	1,610
Area Ratio		625:1
Mixture Ratio	(O_2/H_2)	6:1
Specific Impulse	(Sec.)	482.5
Length	(In.)	94
Maximum Diameter	(In.)	53
Dry Weight	(lb_F)	290
Prop. Flow Rate	$\frac{(\text{Lb Prop})}{(\text{Lb}_{\text{THRUST}} \times \text{Sec})}$	$2.073.10^{-3}$

2.2.3 OTV PERFORMANCE. The OTV baseline is designed to meet all requirements of the MSFC Nominal Mission Model, Rev. 6 October 1982. The two tank aerobraked OTV (Figure 2-10) and four tank aerobraked OTV (Figure 2-11) with an aerobrake) performance capabilities are summarized in Figure 2-13. Total propellant required includes unusable residuals, boiloff losses, start up and shut down losses and Attitude Control System propellant as well as usable main impulse propellant. A gaseous O_2/H_2 ACS is assumed.

The two-tank and four-tank all-propulsive OTV baseline performance capabilities are also summarized in Figure 2-13. The relatively high propellant mass fraction of the all-propulsive vehicle reduces the performance gain for the aerobraked version on the deliver payload mission. The aerobrake offers a significant payload advantage for a return payload (manned mission and GEO satellite servicing are examples) mission.

Figure 2-14 plots total propellant required versus payload delivered to GEO. Straight lines indicate payload delivery capability for partial propellant loads. Solid lines are aerobraked vehicles and the segmented lines are for all-propulsive vehicles. The "Reusable" lines indicate standard payload-delivered-to-GEO-stage-returns-empty operation. Expendable operation includes placing the spent stage in a Debris orbit 2000 nmi above GEO. The Reusable Round Trip Payload mission assumes equal payload up and back.

The all-propulsive vehicle delivers 11% less payload than the aerobraked vehicle on the standard deliver payload mission. On the return payload mission the all-propulsive vehicle delivers less than half the payload of the aerobraked vehicle.

Aerobraked OTV Performance Summary*

	Payload		Total Prop. Required (lb)	Total (lb)
	To GEO (lb)	Return (lb)		
Two tank — payload delivery	11,000	0	28,600	43,950
— return payload	5,880	5,880	28,600	38,830
Four tank — payload delivery	28,700	0	57,140	91,010
— return payload	15,360	15,360	57,140	77,670

All Propulsive OTV Performance Summary*

	Payload		Total Prop. Required (lb)	Total (lb)
	To GEO (lb)	Return (lb)		
Two tank — payload delivery	9,610	0	28,600	40,870
— return payload	2,780	2,780	28,600	34,040
— expendable	16,500	0	28,600	47,760
Four tank — payload delivery	25,800	0	57,140	86,420
— return payload	7,460	7,460	57,140	68,080
— expendable	35,000	0	57,140	95,620

*Maximum capability in each mode

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Figure 2-13 Potential Performance Capability Representative Space-Based OTV

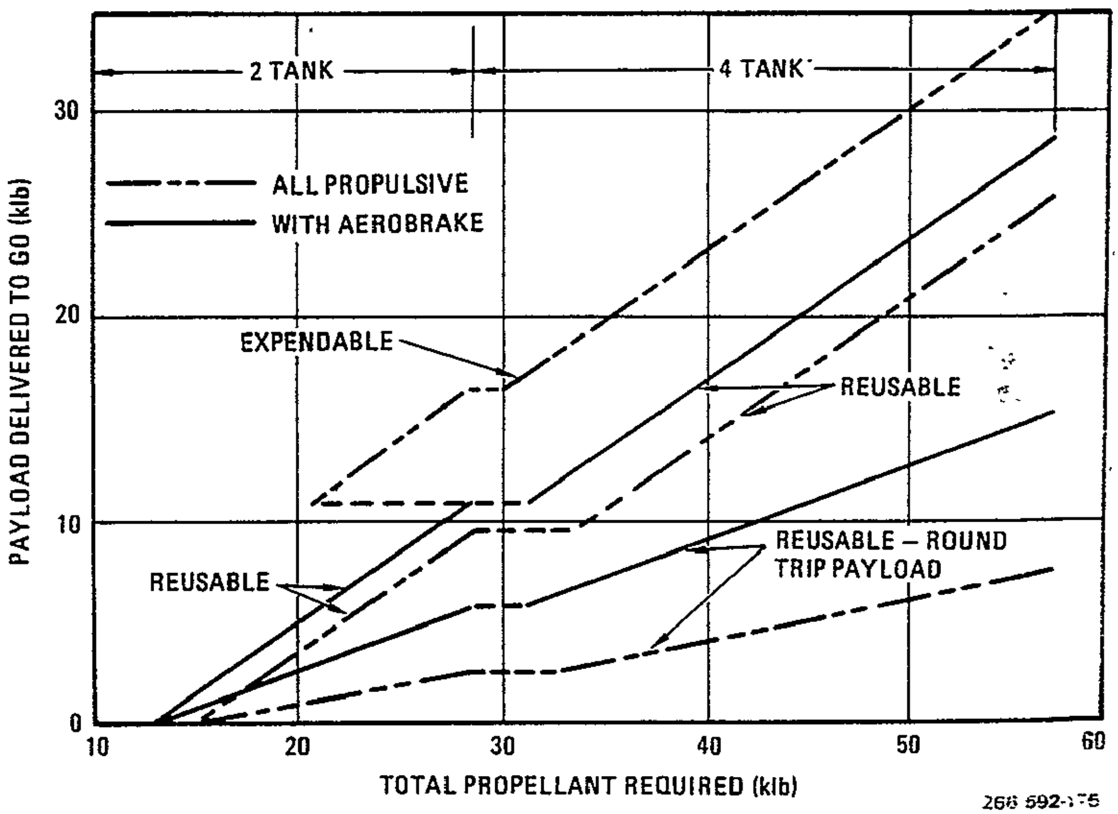

Figure 2-14 Baseline Space-Based OTV Payload Capability

Figure 2-15 plots payload returned to LEO versus payload delivered to GEO. At the extremes, the points along the vertical axis correspond to the standard payload delivery mission tabulated in Figure 2-13 while the points along the horizontal axis depicts a mission where the OTV ascends to GEO with a full propellant load, retrieves a satellite, and returns it to LEO. The dashed line at 45° indicates the return payload mission where payload delivered to GEO is returned to LEO. The all-propulsive vehicle is severely penalized on the satellite retrieval mission, returning less than one-third the payload of the aerobraked vehicle.

2.3 TECHNOLOGY DEVELOPMENT MISSION DEFINITION (APPROACH)

The following are the objectives of this task:

1. Allocate requirements to various major mission elements
2. Generate candidate technology development mission(s) concepts
3. Perform system trade studies to assure viability of the conceptual design
4. Select recommended technology development mission(s) concept
5. Perform an end-to-end functional operations identification analysis
   - Manned/automated functions

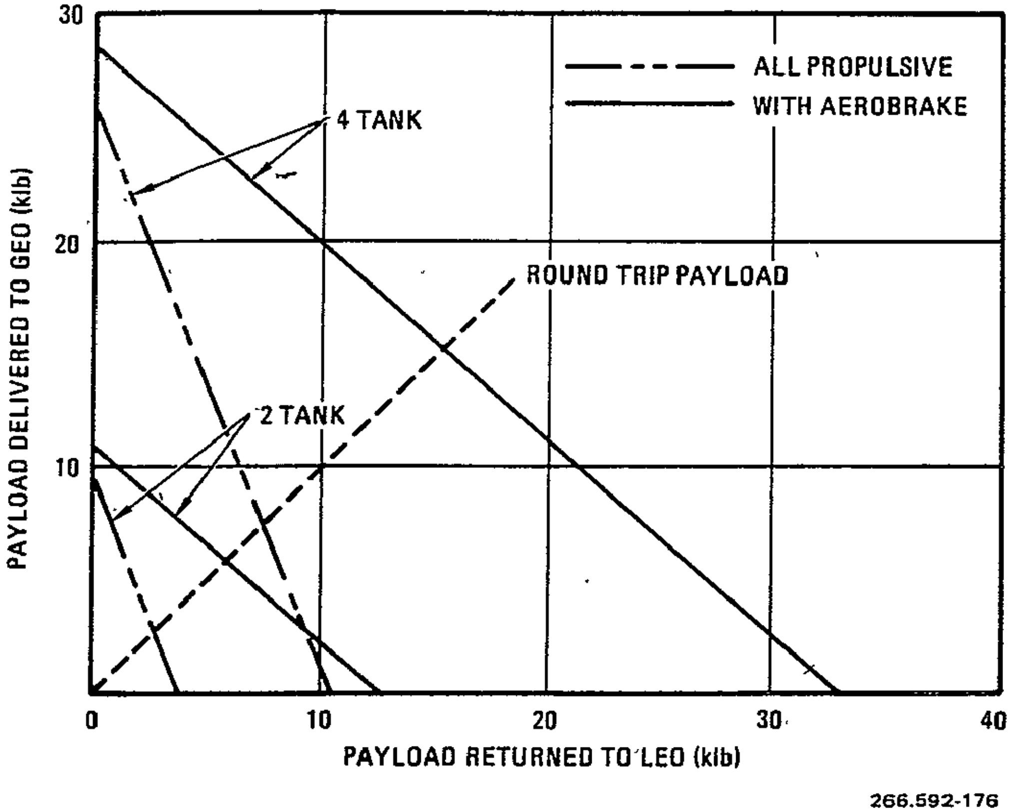

Figure 2-15 Sortie Mission - Return Satellite Payload Capability

- Timelines
- Manpower involvement
- Support equipment
- Task mechanization & implementation

6. Define operational and physical interface requirements between technology development mission(s) and early Space Station

7. Conceptually define special support equipment needed on early Space Station.

Figure 2-16 indicates the approach to Task 2. The input to this task was the Technology Development Mission requirements from Task 1 and our operational experience with ground-launched cryogenic upper stages. Three subtasks are included in Task 2 as shown in the figure. The data generated in Task 2 was inputed to the programmatic analysis task.

The product of this task was conceptual designs and supporting data for technology development missions that must be accomplished on the space station for orderly progression to a space-based OTV capability. Three guidlines were used to influence the scope and nature of the output:

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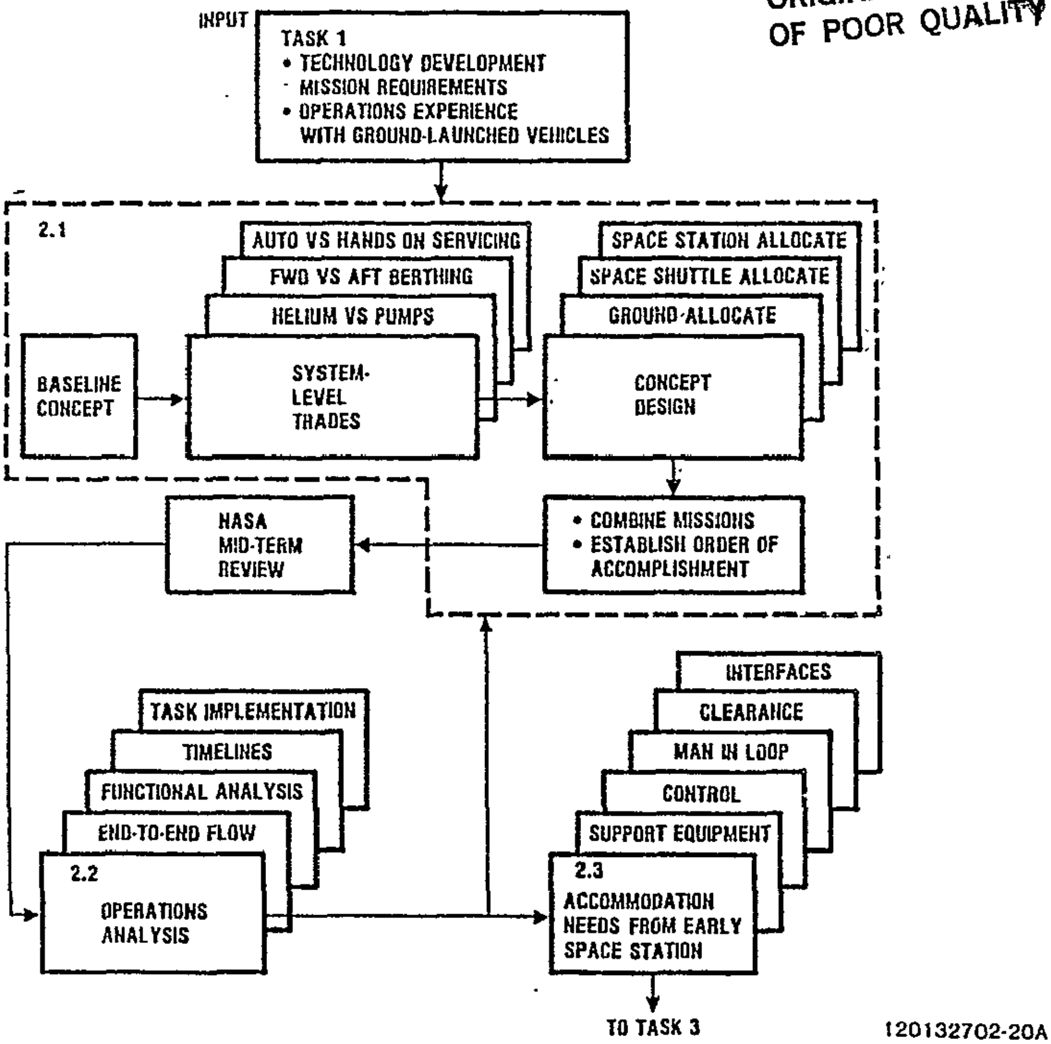

Figure 2-16 Task Flow for Technology Development Mission Definition

- All development that can be accomplished through precursor effort on the ground or in the Space Shuttle will have been identified.
- Whenever possible, missions will be combined to minimize program costs and to maximize opportunity to evaluate system interaction.
- If more than one mission is defined, their accomplishment will be recommended in an order that recognizes immediate and long-term needs.

2.3.1 TECHNOLOGY DEVELOPMENT MISSIONS CONCEPTUAL DESIGN/SYSTEM LEVEL TRADES. Because it is useful for a study as complex as this to have an overall visualization of a space-based OTV system in operation, we used an artist's concept of such a system, as shown in Figure 2-17, to help guide the design of the selected TDMs. The origin of this was not in the current funded space station studies, but resulted from some prior in-house OTV studies. Shown are two OTV servicing stations. The one at the left shows an OTV in a maintenance position housed within a movable servicing hangar. The second view shows an OTV rotated to a position for propellant loading and for payload installation prior to flight. These views were extremely useful for identification of the numerous operations and maintenance functions that are involved in the total scenario.

Using the requirements from Task 1 for the selected functional areas for Technology Development Missions (TDM), the space-based OTV concept defined in Section 2.2, and the concept of operational OTV servicing shown in Figure 2-17, we generated candidate conceptual designs for the TDMs. Alternative designs were generated for each TDM and a combined TDM was also generated. System level trade-off data and inputs from the operations tasks were analyzed during the study in order to arrive at the optimum design for each TDM. This information is contained in Section 3.0 thru 6.0.

Figure 2-18 lists some of the major alternative TDM design approaches considered during the study and the ones we selected.

Our hazard analyses and recommendations for eliminating them (Section 3.2.1) convinced us that LH_2 and LO_2 can be stored and handled on the space station safely, and that you don't have to go to a remote propellant depot with its attendant complications. We also combined the propellant transfer and storage, and reliquefaction functions identified in Task 1 into a single TDM. For the docking tests, we elected to use a modifed TMS because it can perform all the required functions rather than designing a simulated OTV with all the required functions. This is discussed under docking and berthing.

For the maintenance function we elected to use a shelter rather than a presurized enclosure or have the OTV/astronauts unprotected. We believe a shelter should be used for the operational mode to provide environmental protection for the OTV and astronauts.

We investigated a combined mission concept which would require a dedicated shuttle launch rather than individual TDM launches sharing with other payloads. The total shuttle revenue lost is less for the combined mission than for the individual TDM's, but it would mean that all the TDM equipment would have to be developed at one time instead of spread out. (See Section 8.0)

Finally, we analyzed the TDMs for their criticality to developing the OTV servicing capability and prioritized them as shown on Figure 2-19. The criteria used to rank them is also shown on the figure.

The definitions of the TDMs are contained in Sections 3.0 thru 6.0 and are presented in the order shown on the figure.

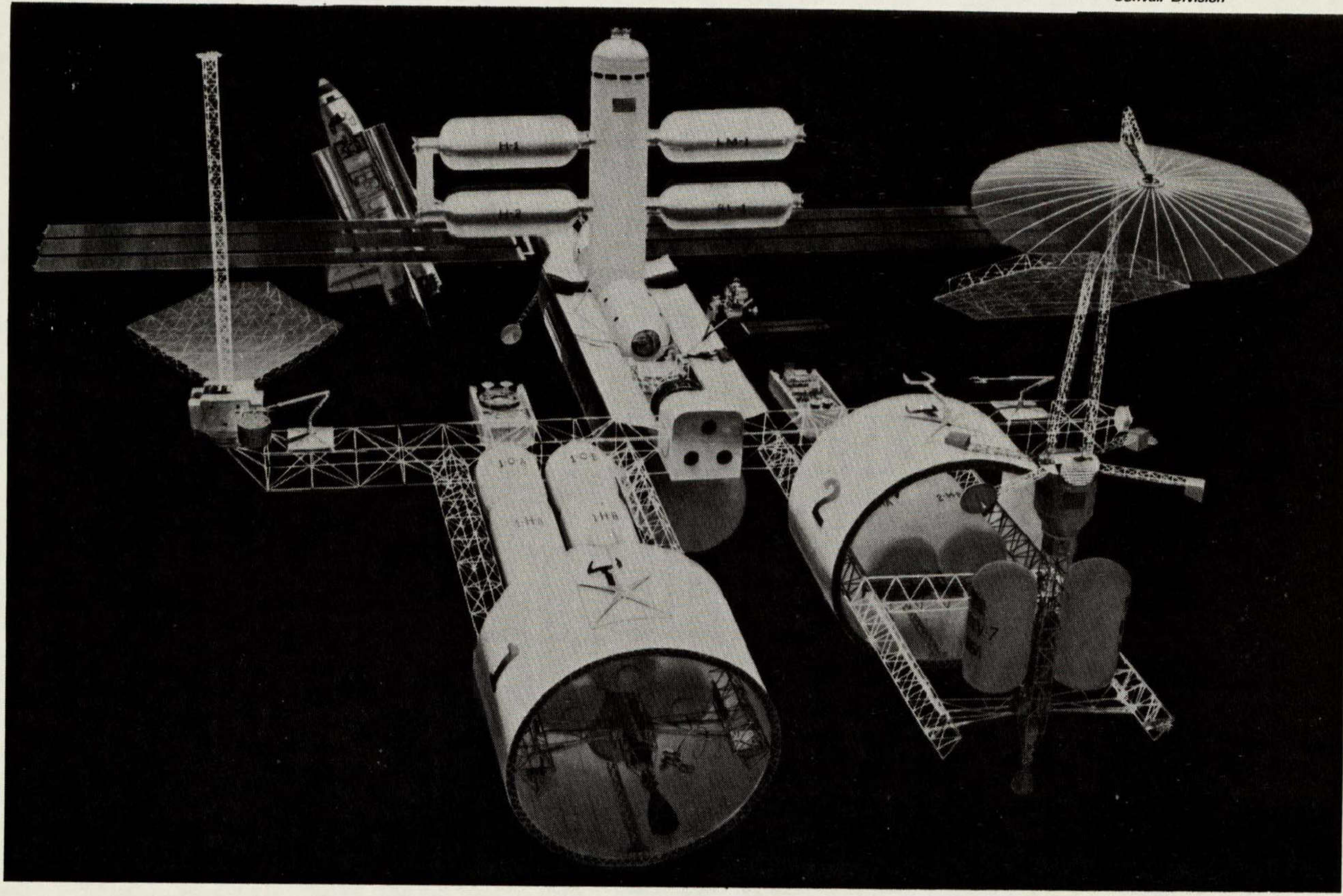

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Figure 2-17 Representative OTV Servicing Concept

Propellant transfer/storage

- Attached to station ✓
- Remote from station

Docking

- TMS ✓
- Simulated OTV

Maintenance/OTV payload operations

- Pressurized enclosure
- Unprotected
- Shelter ✓

Combined mission concept

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✓ Selected

Figure 2-18 Alternative TDM Design Considerations

Ranking order

- Technology development/demonstration
- System design influence
- Operational procedures

Technology development sequence

- Propellant transfer/storage/conservation
- OTV docking & berthing
- OTV maintenance
- OTV/payload integration operations

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Figure 2-19 Selected Technology Development Functional Areas Phasing Priorities

2.3.2 END-TO-END MISSION(S) OPERATIONS. The objective of this task was to analyze the end-to-end operations for the recommended technology development missions. Essentially, this task called for duplicating launch and servicing functions in space that are now performed on the ground. Our experience in launching more than 60 high-energy upper-stage vehicles and in analyzing integration of Centaur into the Shuttle was applied to this task to be certain that realistic and achievable operations and timelines were defined.

We first generated ground rules, assumptions, evaluation criteria, and a maintenance philosophy to guide our operations analysis. We then analyzed functions that must be performed to meet mission requirements and allocated the functions to various elements of the Space Station and OTV. The next step was to establish operations scenarios to meet the major functional requirements. From these scenarios, we established timelines to perform operations.

Scenarios and timelines were generated for both manned and automated functions and combinations, where appropriate, to help determine the manpower/skill and support requirements.

This alternative operations data was used as input to the system trade studies to help select the recommended TDM conceptual design. From our evaluations, analyses, and the system trades, we defined how each operational task would be mechanized and implemented, and the associated manpower and support equipment requirements.

One of the major elements of the space-based OTV operations is the servicing and maintenance functions involving IVA and EVA. To identify these IVA/EVA operations and supporting crews, skills, equipment and scenarios, the analysis approach, shown in Figure 2-20, was directed at identifying a similar or equivalent OTV ground based operations. We feel that the experience we have had with cryogenic upper stages assures that all required tasks have been identified.

These tasks and ground support equipment definitions were then compared to the TDM requirements in conjunction with the IVA/EVA constraints identified in the study.

2.3.2.1 Operational Ground Rules and Requirements. It was important to establish the operational ground rules and philosophy at the beginning of the task so that the analysis could be conducted in a consistent manner. Mission requirements pertaining to operations came from Task 1.3, and the candidate conceptual designs from Task 2.1 (Figure 2-1). In addition to these requirements, for an end-to-end operations definition we had to establish: (1) the maintenance philosophy for OTV servicing and repair; (2) OTV subsystem repair and servicing requirements; (3) ability of the orbital crew to perform the required maintenance and servicing functions in either a shirtsleeve environment or in a space suit; (4) the operations philosophy for the crew on the Space Station; and (5) selection criteria for determining whether tasks should be automated or performed by crewmen.

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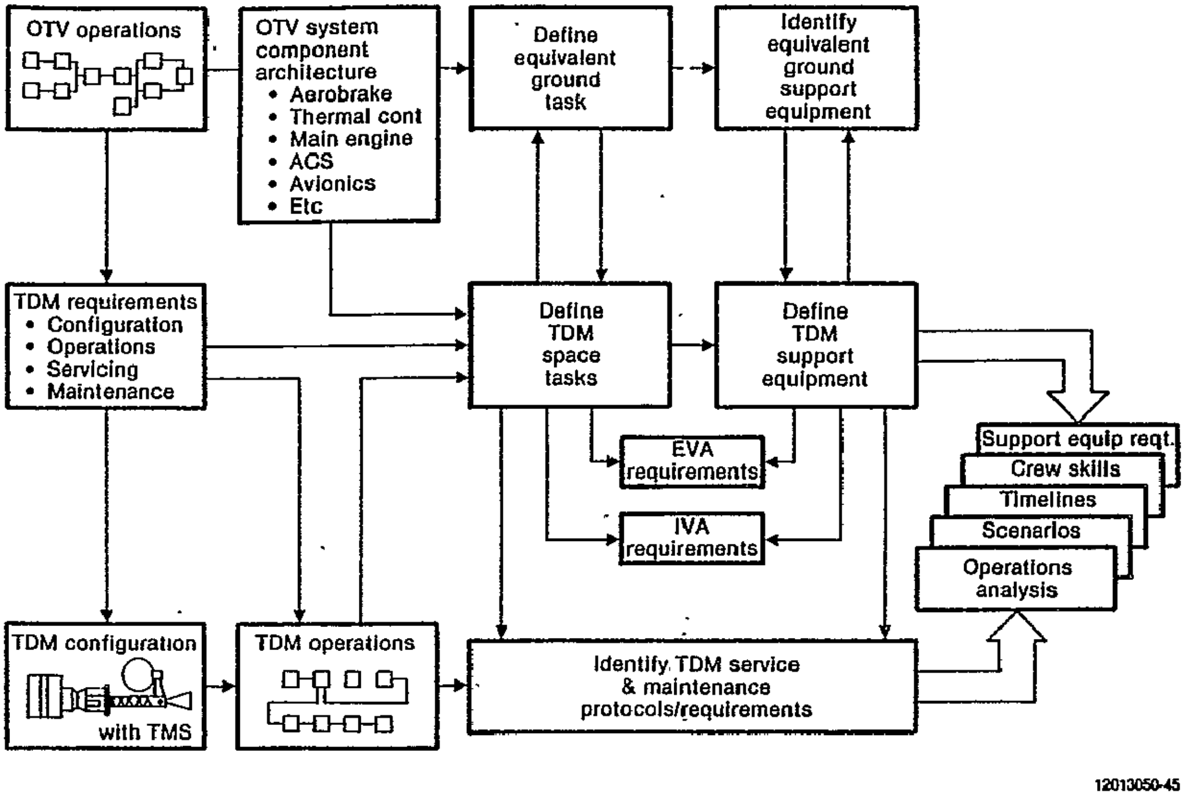

Figure 2-20 End-to-End Mission Operations Approach

For example, we considered airline, military, and Shuttle maintenance philosophies to establish an approach for the operational OTV and, thus, a simulation approach for the technology development mission. The cost of a manhour in space is extremely high so the philosophy we chose tended to minimize manhour requirements.

The major operational ground rules we generated are shown in Figure 2-21. They are a combination of approved NASA Shuttle Flight Operations, EVA ground rules and Space Station philosophies, and NASA references in the RFP. They formed the basis for TDM servicing and maintenance operations analyses during this study.

The servicing and maintenance operations were entirely dependent on Space Station IVA and EVA operations, and subsequently influenced by a) the extent and capability of IVA/EVA, b) the extent and capability of the remotely operated handling and surveillance devices, and c) the man/machine interface compatibility.

A more detailed description of our maintenance philosophy is contained in Section 5.0.

- TDM will provide simulated OTV for proofing space-based OTV operations
- TDM modular components will have realistic interfaces
- A transport system will be available for EVA crew translation to work area
- EVA personnel can operate safely around OTV & propellant transfer area
- On-site propellant leak detection system will provide direct information to EVA personnel
- Information updates provided via head-up displays
- One EVA (8-hour max) mission per day per crew member
- 2-man EVA operations is a requirement for TDM
- EVA conducted in both light & dark environments

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Figure 2-21 Operational Ground Rules

2.3.2.2 Functional Analysis. Using the mission and operational requirements as a basis, we conducted a functional analysis of the technology development mission(s). Functional flows were generated for the end-to-end operations to drive out functional requirements. From the top-level flows, we generated lower-level functions to the level necessary to analyze requirements and establish timelines, methods of meeting requirements, manpower/skills needed, and support system requirements.

When we established the required functions, we evaluated the tasks, calling upon our familiarity with cryogenic upper-stage hardware to determine whether the task should be automated or manned, and the number of manhours required to perform the task on the ground. Since the OTV will be designed to take advantage of space basing, we analyzed the task further to see if, in fact, the design would require fewer equivalent manhours or be changed from a manned to an automated mode. For manned tasks, we determined if the task required EVA or if IVA met the objective. In addition, the number of men and their particular skills were determined. We identified support equipment requirements for tasks to be automated, as well as for manned tasks that require special tools and support equipment.

We incorporated our Centaur operations experience into the study by using people who have worked on Centaur and by consulting with Centaur program personnel.

Definitions of major alternative methods of accomplishing operational tasks was fed into the system-level studies of Task 2.1 (Figure 2-1) to help select the recommended technology development mission(s).

2.3.2.3 Timelines. Timelines for the functional operations identified in the preceding task were generated to further define manpower loading and support equipment requirements. From timelines for required operations and the operational approach ground rules for the space station, an overall schedule was developed for the technology development mission.

The operations tasks are identified for each individual TDM in their respective sections with the major emphasis in the Maintenance TDM in Section 5.0.

2.3.3 ACCOMMODATION NEEDS FROM AN EARLY SPACE STATION. We used the selected TDM concepts to derive requirements for accommodation from an early space station. As in the case made for a fully integrated mission, an awareness of system interactions deeply influences determination of the accommodations that a space station must provide. A generic interface diagram is shown schematically on Figure 2-22, which shows space station elements that interface with the selected technology development missions.

The specific requirements (operational and physical) for accommodations from an early space station included:

- Station/technology mission interfaces
- Berthing structural and control interfaces
- RMS/crane services
- Teleoperator services
- Command center control equipment
- Lighting and video coverage
- Power demand
- Handling equipment
- Maintenance/repair/checkout equipment/tools
- Crewmen skills

Accommodation needs for each TDM are identified in the respective sections with the total identified in Section 7.0.

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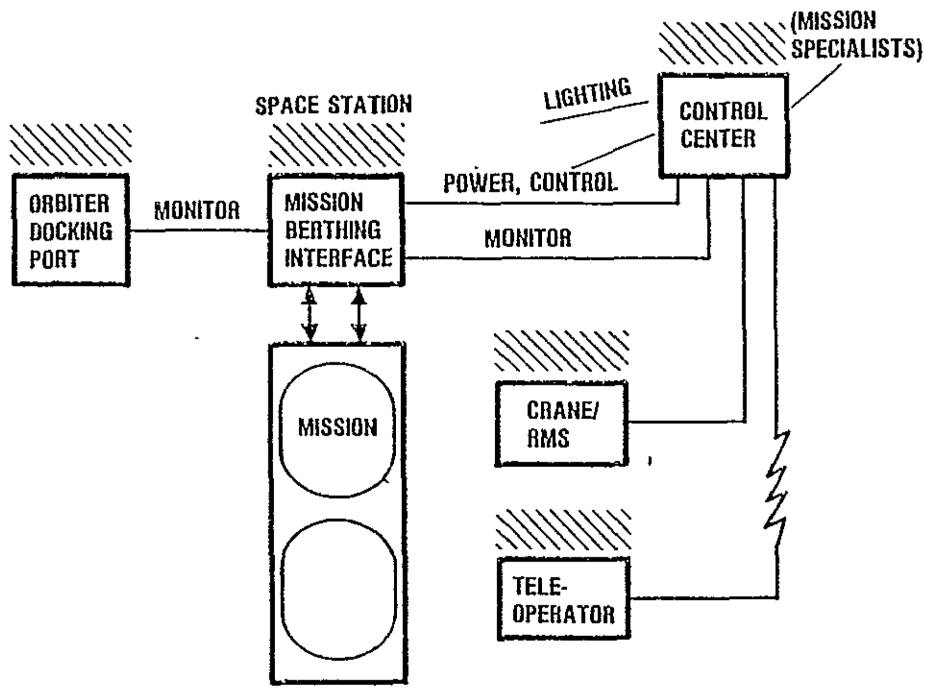

Figure 2-22 Accommodation/Interface Requirements for the Early Space Station will be Identified

3.0 PROPELLANT TRANSFER, STORAGE AND RELIQUEFACTION TECHNOLOGY DEVELOPMENT MISSION

This section defines the selected Propellant Transfer, Storage and Reliquefaction TDM. The definition was generated by performing the tasks as described in Section 2.0 including iterations. The final definition is presented here with some discussion of the iterations performed.

The TDM definition includes: 1) the mission requirements, including a description of the evolutionary technology development plan with the emphasis on the tests to be performed at the initial Space Station, the TDM mission objectives, and mission requirements; 2) the conceptual design; 3) the end-to-end operations and support equipment requirements; and, 4) the accommodations required from the early space station.

3.1 MISSION REQUIREMENTS

The detailed functional analysis of the operational propellant transfer, storage and reliquefaction functions is presented to identify the areas for technology development consideration. Development test matrices are shown indicating what tests should be performed on the ground, in a Shuttle sortie mission, and on the initial Space Station. The rationale for the space station tests is identified. Following this, the objectives and requirements for the space station tests are shown which drive the conceptual design discussed in Section 3.2.

3.1.1 PROPELLANT TRANSFER FUNCTIONS

Figure 3-1 presents the lower level functions which need to be performed in the operation of transferring propellants from a space station to an operational OTV. Similar functions must be performed to transfer propellant to the space station.

We have chosen to consider only LH_2 for the TDM because we feel that if the capability to transfer LH_2 can be developed, these techniques can readily be applied to LO_2.

The following subsections discuss some of the technology requirements of the five major transfer functions which need to be investigated before operational capability can be achieved. Section 3.1.2 describes the evolutionary technology development plan indicating where these investigations should be performed, namely on the ground, on a Shuttle sortie mission, and on the initial Space Station.

Before discussing technology requirements, a representative schematic of a LH_2 propellant transfer, storage and reliquefaction system is presented in Figure 3-2 to help understand the functions being discussed. The system consists of supply and receiver components. Propellant transfer is done by using a pump with a full screen propellant acquisition device. The supply tank con-

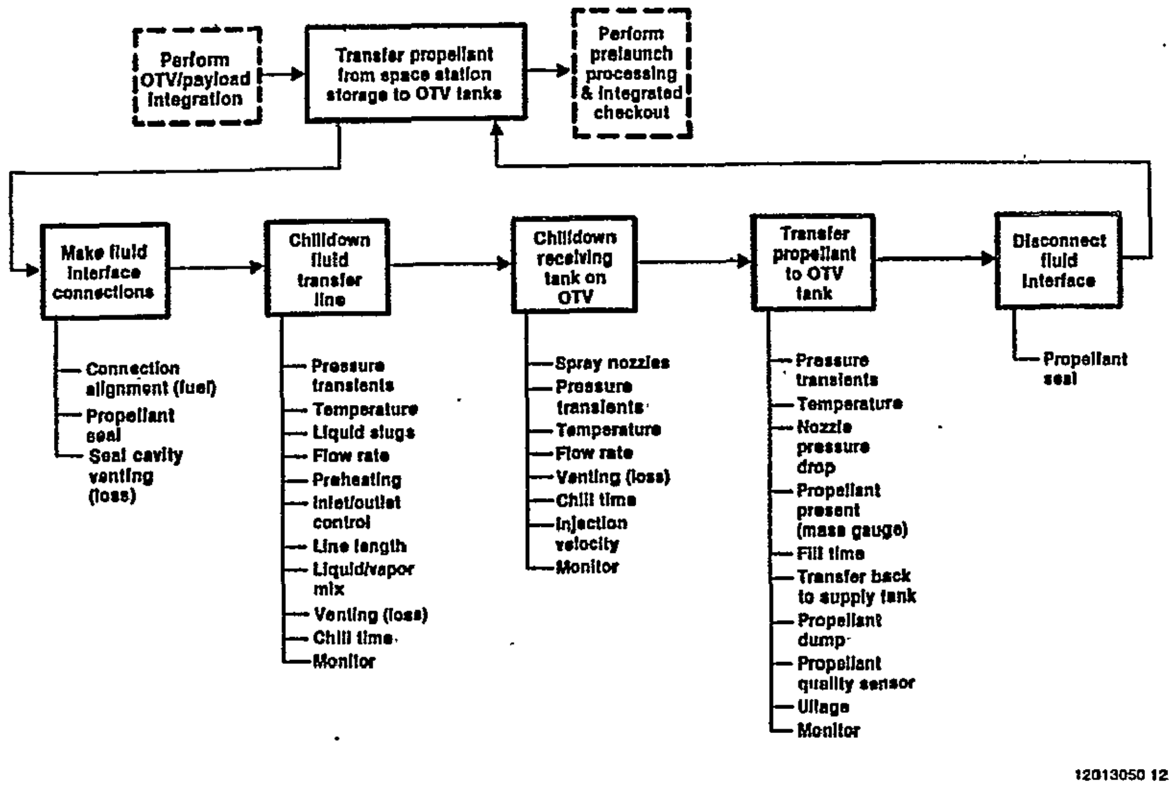

Figure 3-1 Propellant Transfer Functions

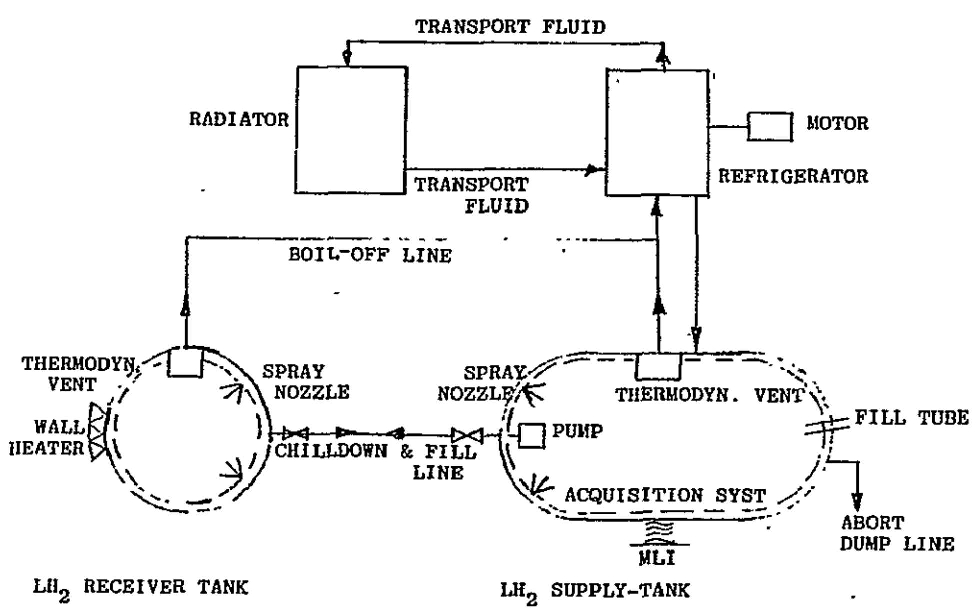

Figure 3-2 Typical Propellant Transfer, Storage and Reliquefaction System

tains subcritical fluid and requires the acquisition device for providing liquid to the transfer line. A thermodynamic vent system provides liquid free venting during storage. Multilayer insulation is required to maintain low incident heat flux to the stored cryogen. The transfer lines are designed for low heat leak and efficient chilldown. The tanks have inlet diffusers and nozzles to minimize vented fluid during chilldown and fill. A reliquefaction unit is used to reliquefy fluid vented from either the receiver or supply tank during storage, transfer and chilldown. The resultant liquid is returned to the supply tank.

3.1.1.1 Docking Fluid Interface Connections. The fluid interface connection is established by a disconnect coupling which connects the LH_2 transfer line between supply and receiver tank. The disconnect coupling must make both structural and fluid seal connections. Prior to selection of the disconnect configuration several design options need to be generated and tested. Several actuating methods involving pneumatics and electro mechanical devices will be included in the trade-offs. Sealing and structural attachments are critical items and will require evaluation. The Shuttle/Centaur cryogenic disconnect coupling configuration could be used as a guide. The operational capability of the cryogenic fluid interface connection configuration and hardware needs to be demonstrated under zero-g conditions. The equipment requires repeated tests of the mechanical connection and sealing capability at the operational pressure and a temperature range between -420 to 140°F.

3.1.1.2 Chilldown of Fluid Transfer Lines. During chilldown, liquid and vapor flow in the transfer line together creating pressure transients. These transients, together with the motion of slugs of liquid in the vapor medium, may transmit damaging loads to the transfer and storage system during the line chilldown period. These loads require evaluation. Therefore, it is desirable to avoid formation of liquid slugs, and pressure surging. It is suggested to meter-in small quantities of the propellant at saturation conditions, probably as a spray to cool the wall at a faster rate. The total amount of heat which must be extracted from the transfer line is easily calculated from the equation:

$$Q = m\, C_V dT$$

where m = mass of line, valves, fittings and insulation

C_V = heat capacity of mass

T = wall temperature

Chilldown time, two-phase flow hydrogen flow rate, LH_2 flow rate and fluid velocity can be determined by conventional methods. An "Orbital Refill Transfer Line Chilldown" program (Ref 3-1) is also available to assist the analysis. The analysis which is more difficult to perform is the dynamics analysis during chilldown and this is the area that must be investigated under zero-g conditions with full scale hardware.

3.1.1.3 Chilldown Receiver Tank. Prechill is accomplished by introducing liquid into the OTV receiver tank at a velocity that provides good heat exchange between the high temperature wall and the cooling fluid. This procedure has the advantage of requiring little mass to effect tank cooling. Chilldown before filling may potentially result in a large propellant loss. Incoming propellant is vaporized when it contacts the warm walls or ullage, causing a sharp rise in pressure which may necessitate venting. Approximately 0.5 to 3% of the final propellant mass could be vented during chilldown depending on the temperature difference between the tank wall and LH_2 temperature. Chilldown losses will be held near the minimum limit by proper design of the inlet configuration. A spray nozzle configuration appears to be the best configuration for achieving high chilldown efficiency. If venting is required, a mechanical liquid-vapor separator (using centrifugal force to separate liquid from vapor) may be used to return liquid to the tank and vent vapor, either overboard, or to the reliquefaction unit. A receiver tank with a large enough scaling factor in zero-g is required to accurately predict the performance of the operational tank.

3.1.1.4 Propellant Transfer to Receiver Tank. Tank fill will be initiated after the prechill requirements have been satisfied. The single requirement for tank fill is to maintain an acceptable low pressure during the process. Tank pressures will be at minimum if thermal equilibrium conditions are maintained during fill.

The intent of the tank fill process will be to create conditions conducive to attaining near-thermal equilibrium. These conditions may be achieved by introducing liquid into the tank through spray nozzles, Figure 3-2. The resulting spray will create a large liquid/vapor surface area. The combination of large surface area and fluid turbulence will provide the high heat-transfer rates needed to attain a near-thermal-equilibrium condition. This must be investigated in zero-g with a tank with a large enough scaling factor to accurately predict the performance of the operational tank.

3.1.1.5 Docking Fluid Disconnect. The operational capability of the total disconnect system needs to be demonstrated under zero-g and required temperature range conditions as described in Section 3.1.1.1.

3.1.2 PROPELLANT TRANSFER EVOLUTIONARY TECHNOLOGY PLAN. Figure 3-3 is an evolutionary technology development plan matrix which identifies the testing level (ground, Shuttle sortie, Space Station) for the functions identified in Section 3.1.1. The rationale for the initial Space Station tests are presented in the figure.

Ground tests should be conducted as an extension of the program we have underway at MSFC with the 87 in. diameter hydrogen tank (References 3-2 and 3-3). These tests would validate the feasibility of some of the candidate options under 1-g conditions. Shuttle sortie tests are required to verify the capability of the options selected from the ground tests. The Cryogenic Fluid Management Facilities experiment being developed by Martin for LeRC or the Orbital Propellant Transfer Experiment defined for LeRC by General Dynamics need to be performed to test zero-g capability. Finally Space Station testing must be performed for the reasons stated on the figure to verify and monitor the thermal and hydrodynamic performance of each system component in the zero-g space station

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Function	Development Tests: Ground	Development Tests: Shuttle Sortie	Development Tests: Station	Rationale for Space Station Test
Make docking fluid interface connection	X	X	X	Dependent on configuration, significantly different from the ground or shuttle tests. Space shuttle envelope is limited
Chilldown fluid transfer line	X	X	X	Space station envelope different from the shuttle configuration. Difficult to parameterize
				Operational transfer line different in length & diameter. The quality of the fluid changes by changing flow rates, length & diameter of line & heat transfer to the fluid. Different pressure surges
Chilldown receiving tank	X	X	X	Chilldown consists of repeated charging, hold & vent cycles until the specified temperature & pressure is reached
				Test tank with the scaling factor of 0.37 is large enough to accurately predict the performance of the operational tank
Transfer propellant to receiving tank	X	X	X	Physical demonstration using operational configuration to maintain thermal equilibrium & low tank pressure
				Determine operational pressure histories, flow rates, number spray nozzles & test instrumentation
Disconnect docking fluid interface	X	X	X	Same as function 1

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Figure 3-3 Propellant Transfer Development Tests Matrix

environment. The major discriminator in the choice between Shuttle sortie and Space Station testing is zero-g testing time, as illustrated from the operational timelines discussed in Section 3.3.

3.1.3 PROPELLANT TRANSFER TDM OBJECTIVES AND REQUIREMENTS. Figure 3-4 identifies the objectives and requirements for the proposed initial Space Station tests. We selected LO_2 tank diameter from our representative space-based OTV (Section 2.2) as the receiver tank diameter for the Space Station tests. This meets the .37 scaling factor number indicated on Figure 3-3 as the ratio to provide accurate prediction of the full scale performance. Thus, many of the test requirement numbers are derived from this specific receiver tank diameter. The test requirements are based on the Space Station operational requirements. If the OTV tank diameter changes, then we would probably want to match its diameter if practical. In this case, the numbers on Figure 3-4 would change. If not practical, we would have to re-evaluate the tank size.

3.1.4 PROPELLANT STORAGE AND RELIQUEFACTION FUNCTIONS. Figure 3-5 presents the lower level functions which need to be performed in the storage and reliquefaction operations at a Space Station to service an operational OTV.

The following subsections discuss some of the technology requirements of the major storage functions which need to be investigated before operational capability can be achieved. Section 3.1.5 describes the evolutionary technology development plan indicating where these investigations should be performed, namely on the ground, on a Shuttle sortie mission, and on the initial Space Station.

Function	Objectives	Requirements
1. Make fluid interface connections	**Demonstrate:** • Mechanical connection • Sealing capability • No propellant loss • Repeatability	• No spillage or leakage • Reusable • Test at operational pressure • Temperature range: −420 to 140F
2. Childown fluid transfer line	**Determine:** • Inlet, outlet, wall temperature • Pressure transients • Fluid quality at outlet • Venting loss • Childown time • Effectiveness of vent system as a source of coolant for line childown • Effect of large quantities of liquid • Heat flux to wall • Loads between tanks	• Spray nozzle at upstream end • Thermocouples along wall • Fluid quality sensor • Pressure transducers to check inlet & outlet pressures • Sensors to record bulk fluid temperatures • Childown time: 30-60 min • Flow rate: 50-100 lb/hr • Precool line with vent gas
3. Childown receiving tank on OTV	**Determine:** • Pressure transients • Fluid flow rate, wall temperature • Quantity of propellant to chill tank • Childown time • Fluid quality at tank inlet • Venting losses • Effectivness of spray nozzles • Heat flux to tank	• Spray nozzle arrays • Instrumentation tree inside tank • Temperature sensors outside wall & penetrations • Run series of cycles, each including an injection, a soak & a vent period • Childown flow rate 50-100 lb/hr • System childown time: 1-72 hr
4. Transfer propellant to OTV tank	**Determine:** • Line & wall temperatures • Fluid pressure & quality • Flow rates • Fill time • Fill level • Supply tank pressurant requirement	• Flow-through spray nozzles • Fluid quality flow meter • Mass gauging device • Temperature & pressure sensors • LH_2 in tank: 750 lb • Fill flow rate: 250-180 lb/hr • Fill time: 3-4 hr • Tank pressure: 18-25 psia • Full screen acquisition system
5. Disconnect docking fluid interface	**Demonstrate:** • Mechanical disconnection • No propellant loss	• No spillage

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Figure 3-4 TDM Objectives & Requirements — Propellant Transfer

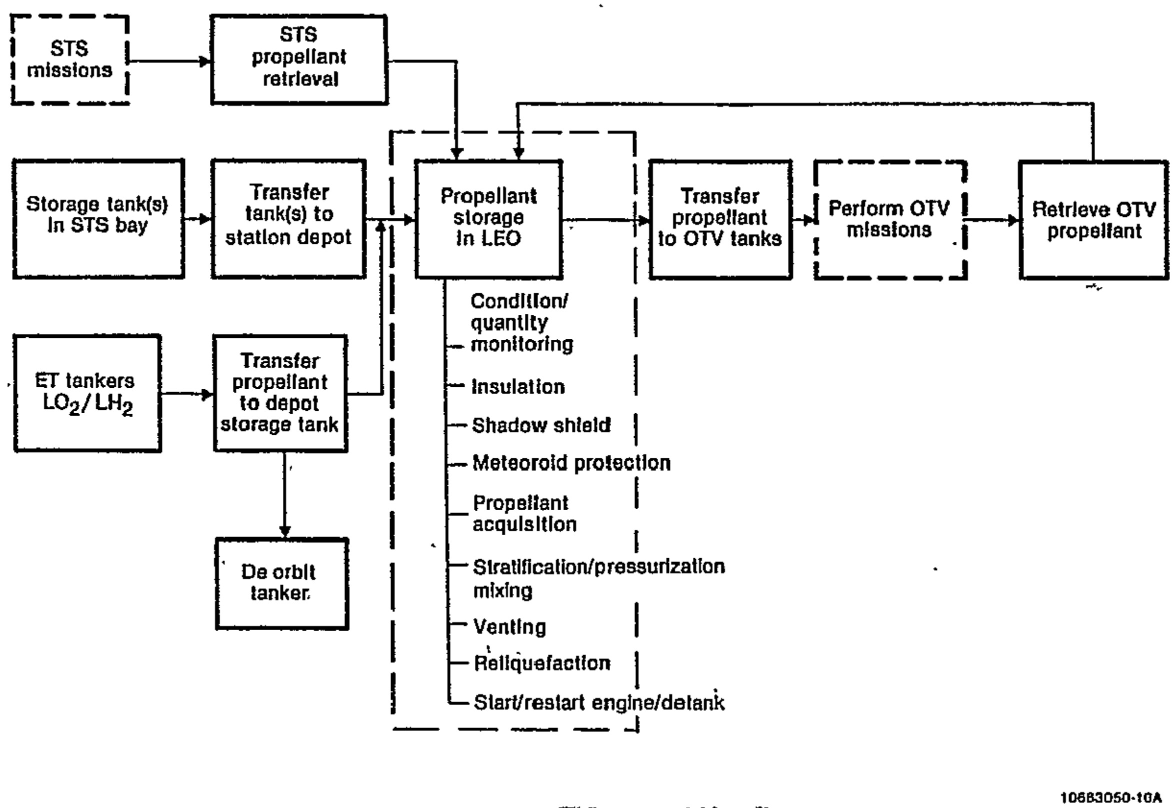

Figure 3-5 Propellant Storage Functional Flow

3.1.4.1 Condition, Quantity and Monitoring. For the cryogen storage concept, the following conditions were assumed:

1) Cryogen storage is at 216 NMI. (Nominal Space Station Orbit)

2) Maximum disturbance is 10^{-5} g for station keeping.

3) Tank is shadow shielded.

4) System will function 20 years.

5) Safety is absolutely essential.

6) Transfer is automated.

7) Storage is monitored by Space Station crew.

3.1.4.2 Insulation. The insulation to be used for the cryogen storage tanks consists of 45 layers of "Superfloc", 1.5 inch thick multilayer insulation (MLI). Superfloc is a Convair and NASA/MSFC developed high efficient, light weight multilayer insulation in which the coated aluminized kapton radiation shields are separated by low conductive Dacron needles. For this program a multilayer insulation system was selected for the thermal protection system. The other alternative considered was a combination of MLI and vapor cooled shields. It is suspected, however, that a "possible" improved performance will not compensate for the weight addition.

3.1.4.3 Shadow Shields. Shadow shields are suggested to keep the supply tanks in the shadow. The shield system would be located at some predetermined distance from the tanks, facing the radiation source with foils which are highly reflective on both sides. The shield spacing should be relatively large so that each shield can radiate to space instead of to its neighbor. Reference 3-4 suggests that four shadow shields space 1/10 of a tank diameter apart are thermally equivalent to 30 shields spaced 1/1000 diameter apart. The disadvantage of the shadow shield is the large target they present to meteoroids.

3.1.4.4 Meteoroid Protection. Meteoroids are solid particles moving in space which originate from both cometary and asteroidal sources. Thin radiation shields which cover the supply tank and the propellant transfer system, if unprotected, are vulnerable to meteoroids. Meteoroid impact may also deteriorate optical surfaces and thermal balance coatings, or may reduce the heat shield effectiveness. Another possible impact effect includes damage of the refrigeration system radiator. Present knowledge of both the occurrences and physical properties of meteoroids and space debris will be considered for the design of the propellant storage system. It is suggested to use a double skin aluminum alloy or a honeycomb system for meteoroid protection.

3.1.4.5 Propellant Acquisition. In zero gravity the position of the liquid vapor interface is uncertain. Capillary acquisition devices were selected as the baseline propellant acquisition system because they are highly reusable, inherently passive and relatively low in weight. These devices use fine mesh screens (200 x 600 Mesh Woven wire) to contain propellant within channel or liner configurations. Surface forces keep vapor from penetrating the screens. Sufficient screen area is used so that the screen devices can be in contact with the main pool of liquid during draining. MSFC is testing a GD/Convair designed acquisition system during the 1983/84 test activities with an 87 inch diameter tank, under contract NAS 8-31778, at Huntsville, Alabama (Ref. 3-5). Further development and flight tests are required to confirm the function of capillary systems in cryogenic propellants.

3.1.4.6 Stratification, Pressurization and Mixing. The undisturbed supply tank when filled with LH_2 will tend to stratify according to the fluid temperature. The liquid temperature at the liquid vapor interface determines the pressure in the system. Pressure rise data and/or vent and pressurant requirements during orbital storage are required. Stirring of the stratified hydrogen will tend to create a uniform temperature throughout the liquid and will cause a pressure drop. It is necessary to evaluate the effectiveness of mixing on a full scale tank over a long term in the space environment. Fluid mixing basically destroys fluid temperature stratification thus minimizing the pressure rise. It also may eliminate the need for venting at low-g. Mixing is also used to minimize or eliminate vapor formation within, or at the surface of a screen type acquisition system.

Pressurization during propellant transfer tests will be autogenous. This type of pressurization has been selected because 1) it is simple and a proven approach, and 2) the alternative helium pressurization approach would be considerably heavier and require helium resupply. This type of pressurization was analyzed in contract NAS 3-20092 (Ref. 3-5).

3.1.4.7 Venting. A thermodynamic vent system will provide vent capability for the system. A vent system has been designed by GD/Convair. It will be tested during the 1983/1984, MSFC/GDC test activity, under contract NAS 8-31778, utilizing the GD/Convair 87 inch tank (Ref. 3-5). Prior to transferring propellant the tank will be vented to 2 - 4 psia. This step is performed to minimize peak pressures and the number of charge and vent cycles required during prechill. The vent rates can be reduced, if necessary, by adding more layers of MLI. There was no alternative vent system considered.

3.1.4.8 Reliquefaction. Orbital boiloff will not be lost. Reliquefaction units which draw power from the space station will recycle all boiloff (Figure 3-2). Reliquefaction of boiloff uses less energy than initial liquefaction since the boiloff is at or near cryogenic temperature. Heat rejection is accomplished by radiation to space. The radiator configuration must be evaluated for on-orbit assembly/deployment techniques, transport fluid, coatings, damage/leakage due to micrometeoroids, maintenance, as well as the influence on overall thermodynamic system efficiency. A discussion of flight type refrigeration units is presented in Section 3.1.7.

3.1.4.9 Start/Restart Engine/Detank. The acquisition system is designed to provide gas-free liquid in the zero-g environment and to assure simulated start, restart and detank conditions. Tank pressure P's for start, restart and detank tests will be selected to meet operational requirements.

3.1.5 PROPELLANT STORAGE EVOLUTIONARY TECHNOLOGY PLAN. Figure 3-6 is an evolutionary technology development plan matrix which identifies the testing area (ground, Shuttle sortie, Space Station) for the functions identified in Section 3.1.4. The rationale for the initial Space Station tests are presented in the figure. Some of the functions are not recommended for testing in the Shuttle because of duration considerations.

Ground tests should be conducted as an extension of the program we have underway at MSFC with the 87 in. diameter hydrogen tank (References 3-2 and 3-3). These tests would validate the feasibility of some of the candidate options under 1-g conditions. Shuttle sortie tests are required to verify the capability of the options in some functions selected from the ground tests. The Cryogenic Fluid Management Facility experiment being developed by Martin for LeRC or the Orbital Propellant Transfer Experiment defined for LeRC by General Dynamics need to be performed to test zero-g capability of the functions shown in the figure. Finally, Space Station testing must be performed for the reasons stated on the figure to verify and monitor the thermal and hydrodynamic performance of each system component in the zero-g space station environment. The major discriminator between Shuttle sortie and Space Station testing is zero-g testing time, as illustrated from the operational timelines discussed in Section 3.3.

3.1.6 PROPELLANT STORAGE TDM OBJECTIVES AND REQUIREMENTS. Figure 3-7 identifies the objectives and requirements for the proposed initial Space Station tests. The selection of the 84 in. diameter receiver tank, discussed in Section 3.1.3, and the fact we selected three times the receiver tank quantity for the storage tank, accounts for some of the numbers on the figure. Other numbers are based on actual Space Station operational requirements. Propellant acquisition system requirements will be determined after operational predesigns have been performed.

Function	Development Tests: Ground	Development Tests: Shuttle Sortie	Development Tests: Station	Rationale for Space Station Test
Condition/Quantity monitoring	X	X	X	Thermo/Hydrodynamic operational exp analysis
Insulation	X		X	Demonstration of thermal performance of an operational MLI & attachments. Space station mounting & tank penetrations are different from previous tests
Shadow shielding	X		X	Refine ground design to achieve lowest propellant loss. Shield spacing is large. Each shield radiates to space instead of only to its neighbor
Meteoroid protection	X		X	Thin radiation shields if unprotected are vulnerable to meteoroids. Should shields be penetrated the thermal performance of the MLI is reduced
Propellant acquisition	X	X	X	Full screen acquisition device, completely passive; conceptual design available. Flight test in the late 80s
Stratification/Pressurization/ Mixing	X	X	X	Stratification causes liquid/vapor interface problems, thus increasing heat transfer between L&V, may result in ullage pressure collapse
			X	Mixing required to destroy fluid temperature stratification, minimizes pressure rise, lowers need for venting
Venting	X		X	Thermodynamic vent system. Liquid venting would impose intolerable weight penalties
Reliquefaction	X		X	The Stirling or Brayton cycle refrigerator will be used based on lowest equipment weight & volume per kW refrigeration requirement, projected maintenance-free operation & development history & availability
Start/Restart engine Detank	X		X	The acquisition system is the key element for providing gas-free liquid in the zero-g operational environment

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Figure 3-6 Propellant Storage Development Tests Matrix

Function	Objectives	Requirements
1. Condition/Quantity monitoring	**Evaluate:** • Sensors to measure temperature, pressure, fluid quality & quantity in zero-g environment	• Internal pressure: 18-25 psia • Tank fluid quantity: 2,032 lb • Tank wall temperature: 37R • Pressurization with GH_2
2. Insulation	**Determine:** • Performance of the thermal protection system exposed to solar radiation in LEO • Boiloff rates • Heat flux to tank	• MLI (40 to 80) radiation shields • Blanket pin attachments • Low conductive supports & penetrations • Low system weight • Low boiloff rate
3. Shadow shield	**Determine:** • Thermal performance of function 2 test using one shadow shield • Boiloff rates & compare with function 2 test • Performance using 2 shadow shields	• Reinforced ALU shield • 1/10 of tank diameter spacing • Low conductive support
4. Meteroid protection	**Monitor:** • Long-term performance of the thermal protection system	• Use 1/32 ALU shield to prevent erosion of thin radiation shields • Ensure retention of coating properties

Figure 3-7 TDM Objectives & Requirements — Propellant Storage 10063050-81A

Function	Objectives	Requirements
5. Propellant acquisition	**Demonstrate:** • Initial filling, liquid expulsion & refill capability • No vent fill • Liquid-free venting **Determine:** • Accuracy of mass gauging during fluid transfer • Propellant losses	• Full screen acquisition device • Expelling gas-free liquid in zero-g • Liquid-free venting • Consider available conceptual designs • Tank pressure: 18-25 psia • Mass gauging device accuracy: ±1% to ±3%
6. Stratification/ pressurization/ mixing	**Evaluate:** • Effectiveness of fluid mixing for long-term storage using thermodynamic vent system • Jet mixers to reduce stratification **Establish:** • Pressure rise data & tank fluid & wall temperatures	• Control thermodynamic state by fluid mixing. • Use thermodynamic vent system with mixer • Consider jet mixers, electric motor driven with low power consumption • Basically reduce stratification by mixing
7. Venting	**Determine:** • Thermodynamic vent system effectiveness in space **Monitor:** • Bulk heat exchanger temperature • Vapor return to reliquefaction system • Tank pressure	• Thermodynamic vent system with heat exchanger & mixer • Liquid-free venting • Tank pressure: 18-25 psi
8. Reliquefaction	**Verify:** • Performance of the total system using a Stirling or a Brayton cycle refrigeration system **Determine:** • Propellant quantity reliquefied	• Use Stirling or Brayton cycle refrigeration system • Low equipment weight & volume • Available & maintenance-free equipment • Space radiator & solar array • Expel gas-free liquid
9. Start/Restart Engine/detank	**Demonstrate:** • Propellant acquisition system performance in zero-g • Capability of system integrated with operational tank pressure control system • Propellant unloading in zero-g	• Expel gas-free liquid

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Figure 3-7 TDM Objectives & Requirements - Propellant Storage (cont)

A further discussion on the reliquefaction system is presented in Section 3.1.7.

The requirements shown in Figures 3-4 and 3-7 were used to drive the TDM design discussed in Section 3.2.

3.1.7 RELIQUEFACTION. The use of a reliquefaction unit is a key to low propellant losses. For specific requirements, a trade study would determine cost effective reliquefaction capacity vs insulation system including shadow shields.

Weight, volume and maintenance-free operation time are presented in Figure 3-8 for four thermodynamic refrigeration cycles. The Braydon and Stirling cycles are considered for the Space Station reliquefaction system. The selection will be based on low system volume and weight, maintenance-free operation and low power requirement.

3.1.7.1 Refrigeration Requirements. This section presents a preliminary calculation on refrigeration requirements which are needed for hydrogen boil-off reliquefaction for the TDM.

The amount of power needed for reliquefaction of 1 lb/day of hydrogen = 2.37 watts (Ref 3-8). Cooling needed to reliquefy the boiloff from the supply and receiver tank:

0.27 lb/hr +.13 lb/hr = 0.40 lb/hr = 9.6 lb/day

The cooling needed to reliquefy 0.4 lb/hr:

$$(9.6 \text{ lb/day})\ 2.37 \ \frac{\text{W}}{\text{lb/day}} = 22.75\text{W}$$

Reliquefaction rate is $\frac{22.75 \text{ W-hr}}{0.4 \text{ lb}} = 55.88 \ \frac{\text{W-hr}}{\text{lb}}$

Nominal cooling desired:

Supply tank + receiver tank

$$^{*}51.0 \ \frac{\text{BTU}}{\text{hr}} + {}^{*}24.6 \ \frac{\text{BTU}}{\text{hr}} = 75.6 \ \frac{\text{BTU}}{\text{hr}}$$

in watts = 75.6 x 0.2930 ≒ 22 W

Design cooling 10% margin = 24 W

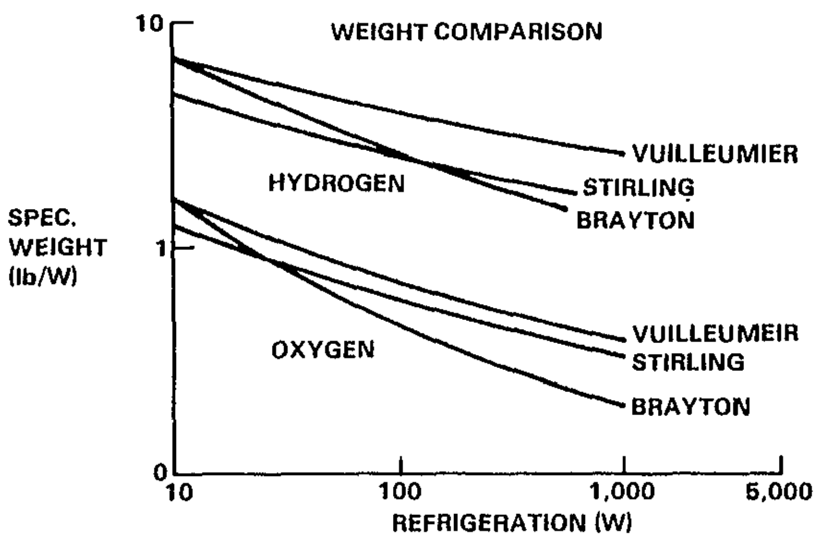
Nominal cooling tem. 20°K

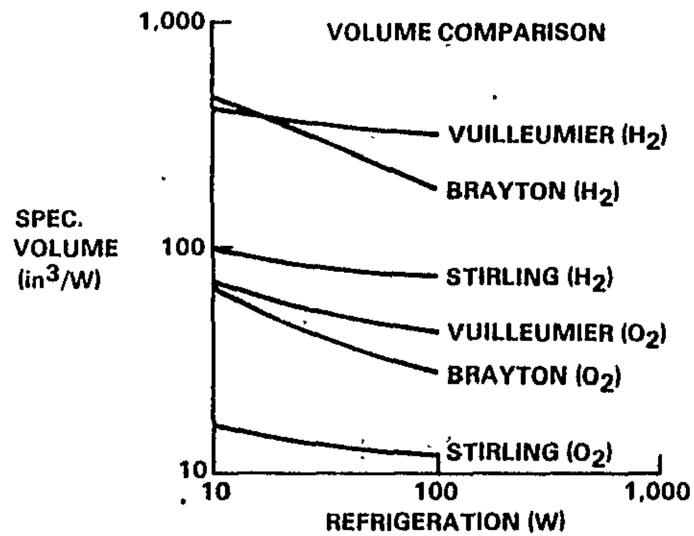
Cooling range 17-23°K

Coef. of performance C.O.P. $= \frac{\text{Q Refr}}{\text{W input}} = \frac{T_c}{T_h - T_c}$ carnot

*Data based on results from GDC 87" dia experimental tank using supply and receiver tank surface areas.

Thermo-dynamic Cycle	3.55 kW Refr. at 20°K		7.13 kW Refr. at 77°K		Projected Maint. Free Oper. Hrs	Assessment	
	Spec. Wt. lb/watt	Spec. Vol. in^3/watt	Spec. Wt. lb/watt	Spec. Vol. in^3/watt			
Brayton	1.45	50	0.185	17	1,000	Lowest weight & volume at higher kW refrigeration requirements. Gas bearing refrigerator promises long life. Long development history	
Stirling	2.0	70	0.265	20	1,000	Long development history. Low power consumption.	Present crankcase bearing system limits life. Regenerators sensitive to fouling.
Vuilleumier	2.3	300	0.310	36	1,000	Can use solar heat directly.	No operational experience. Little test data.
Gifford-McMahon Taconis Solvay	3.4	400	0.450	55	5,000	Fully developed. Used on aircraft. Unit is simple. Components can be separated.	





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Stirling or Brayton cycle will be selected based on lowest equipment weight & volume 12013050-21

Figure 3-8 Liquefaction Cycle Options

Assume max temp T_h = 300°K

T_c = 20°K

$$COP = \frac{20}{300-20} = 0.071$$

The power input for reliquefaction $= \frac{24}{0.071} = 338W$

Spec Weight = 2 lb/WATT (Ref 3-8)

Total Refrig. Weight = 676 lb

Spec Volume: 70 in^3/Watt

Refrig. Volume: 23660 in^3/Watt = 13.7 ft^3

Waste heat radiator: $\approx$ 200 ft^2

Power supply: Photovoltaic area on space station or erectable panel type configuration.

3.1.7.2 Cool Down of the Refrigerator. Cool down time of a refrigerator, where the mass is relatively high and where intermittent operation is desirable, can be an important consideration. For the intermittent operation case, all heat exchange elements and fluid cooling systems must be cooled down to operating conditions prior to efficient propellant refrigeration.

3.1.7.3 Coefficient of Performance (COP). The COP decreases substantially as the unit becomes small because higher heat leaks are present, components are more difficult to fabricate, unfavorable area to volume ratios result, and frictional losses are higher. The COP we are using is so low because there are so many components involved, such as heat-source, heat sink, mechanical refrigeration and mechanical work source. The refrigerator has a compressor, expander and motor. These components contribute to the low C.O.P.

3.2 CONCEPTUAL DESIGN

The recommended TDM conceptual design is presented along with a preliminary weight statement. As the study progressed, it became evident that a combined TDM to meet the propellant transfer, storage and reliquefaction requirements was the most efficient approach and that is the design presented here. In addition, the results of our safety analysis is presented.

3.2.1 SAFETY ANALYSIS. A preliminary hazard analysis was undertaken to examine the safety aspects of storing and transferring LH_2 and LO_2 aboard the Space Station for the fueling of a space-based OTV. This was done in order to determine if LH_2, to accomplish the Propellant Transfer, Storage and Reliquefaction TDM, could be stored safely at the station, and that a separate free flying propellant depot would not be required. Potential hazards were identified and recommendations to eliminate these hazards were developed. From the results of the analysis, we feel that the LH_2 can be safely stored at the station if the recommendations are incorporated into the design of the TDM.

Table 3-1 is a summary of the results of our safety analysis. The major potential hazards are listed along with the recommended approaches to eliminate each hazard. In evaluating the recommendations to eliminate the hazards, we came to the conclusion that the TDM equipment could be designed, following the recommendations in Table 3-1, so that it could be attached to the initial Space Station.

3.2.2 RECOMMENDED DESIGN. Figure 3-9 shows the recommended propellant transfer, storage and reliquefaction TDM design along with a preliminary weight statement.

The equipment follows the system schematic shown in Figure 3-2. The requirements generated in Section 3.1.1 and 3.1.2, along with the design recommendations from our safety analysis, were used as the design drivers of the system. In addition, the size of our receiver tank was obtained from the performance baseline space-based OTV described in Section 2.2. The size of the LO_2 tank from that analysis turned out to be 84 inches in diameter. This is approximately .37 times the volume of the required LH_2 capacity. From our experience with LH_2 testing, and the size of the test tank (87 in. dia) being tested at MSFC presently, we determined that the capacity of the LO_2 tank would be ideal for the receiver tank for our proposed TDM. The launch configuration of the TDM is shown in two views on Figure 3-9, along with the equipment attached to the Space Station and the radiator deployed. The Space Station interface is discussed in Section 3.4.

The propellant transfer, storage and reliquefaction TDM consists of one spherical receiver tank, one cylindrical supply tank with spherical bulkheads, a propellant conservation (refrigeration) unit, a RMS, an open truss support structure, a propellant transfer system (pump and lines), electrical lines, interface electronics and Shuttle interface plumbing. Each tank has an acquisition system and multi-layer insulation (MLI). Both tanks are

Table 3-1 Potential Cryogenic Hazards and Recommended Elimination Approaches

Item #	Hazard	Recommendation
1.	Foreign object collision puncturing a cryogen tank causing unbalanced reaction forces.	Shielding of the tanks Capability of jettison of tanks Provide opposite reaction forces with reaction control system.
2.	Ignition of cryogenics above 100,000 feet in altitude.	Given the properties of space, it is unlikely that cryogens will ignite, because there is not enough pressure to supply combustion.
3.	Leakage during refueling, possible cryogen freezing.	Use no-leak connections and purge any lines exposed to space atmosphere.
4.	Cryogenics in fuel transfer lines, could freeze and block line.	Insulation of any exposed cryogen lines should prevent inline freezing of cryogens.
5.	Liquid cryogens escaping into space become gaseous. (80% vapor, 20% solid)	Because of solar heating effect on surfaces, gas should not stick to structures and eventually dissipates into space.
6.	Cryogens on EVA support equipment, causing ice up of life support systems.	Proper heating should avoid ice up.
7.	Defective or damaged sealing surfaces, causing cryogen leakage.	The inspection of sealing surfaces and seals prior to installation. Materials selected must be compatible with cryogenic temperatures and redundant sealing devices provided.
8.	Cryogen leakage due to inadequate torque, caused by improper application, relaxation, temp. change/cycling and mechanical loading.	Engineering approved and controlled procedures will be used in all torque applications and connection designs should not be sensitive to the torque of the fasteners.
9.	Explosion due to a cryogen tank overpressurization.	a) place pressure relief valves at strategic points on each pressure vessel or line, hose or pipe that may become isolated and entrap cryogen gas/liquid.

Table 3-1 (cont)

Item #	Hazard	Recommendation
		b) Cryogen storage vessels should have sufficient redundancy to prevent overpressurization. c) If vacuum insulated components are used the inner and outer shells of the cryogen vessels should be evacuated to maintain insulation. The annular space should be designed with consideration to the hazardous effects of a potential cryogen leakage into the annulus. d) Pressure relief discharge lines should be of sufficient size so that they don't restrict the relieving capacity of the safety device. e) Relief devices should be far enough from the tank so that they do not ice up/freeze over and become ineffective. f) Pressure/storage vessel shall meet ASME Code, Section VII, Div. 1 and 2 or MIL-STD-1522. Vessels shall also meet requirements of NSS/HP-1740.1.
10.	Explosion due to debris inside a cryogen tank which might clog a valve or block a line.	Cryogen systems should be free from any impurities in accordance with MSFC-SPEC-164.
11.	Contamination of the cryogens through relief valve openings, allowing the entrance of contaminants.	Relief valves should be provided with protective devices to prevent the entrance of contaminants.
12.	Explosion in a cryogen tank due to the lack of impact sensitivity.	Cryogens should be evaluated for impact sensitivity in accordance with MSFC-SPEC-106.

Table 3-1 (cont)

Item #	Hazard	Recommendation
13.	Fire/Explosion due to a transducer ignition near any cryogens.	Transducers in contact with any cryogen should have damping oils emitted and calibrated as "dry" units.
14.	Injury/Explosion due to the non-insulation of any manual control valves.	Manual control handles of cryogenic valves should be insulated so as not to be hazardous to an operator.
15.	Leakage/overpressurization caused by failure of a valve.	Valve housing design should prevent vapor pressure buildup as a result of cryogen leakage into the valve housing.
16.	Explosion of a cryogen storage vessel while pressurizing to a safe level.	Design of pressure vessel shall include the capability of returning the system to a safe condition at anytime during ground or flight operations.
17.	Contamination/personnel injury due to the failure of any prefabricated components, such as pumps, regulators and valves.	Prefabricated components shall have proof and burst rating that are adequate. Hardware that is returned to Earth shall be designed to withstand repressurization by the atmosphere.
18.	Contamination/injury/illness due to the failure of pressure sensors.	Accurate sensors should be used to make sure pressure is totally relieved before maintenance and checkout of cryogen tanks.
19.	Explosion/fire, contamination due to structural instability of a cryogen tank.	The structural stability of a pressure vessel should not be dependent on the tanks being pressurized.
20.	Explosion/Fire, ignition of fuel due to improper grounding.	Equipment which can transmit sparks or generate static electricity should be properly grounded.

Equipment	Wt (lb)
Receiver tank	95
Receiver tank acquisition system	65
Receiver tank MLI	25
Supply tank	170
Supply tank acquisition system	230
Supply tank MLI	108
Transfer lines	182
Data control & interface electronics	290
Electrical system	190
Shuttle interface lines	162
Supporting truss structure	580
Space station controls & displays	170
RMS	350
Propellant reliquefaction body structure	200
Propellant reliquefaction equip	600
Radiators	450
LH_2	2,032
Total	5,899

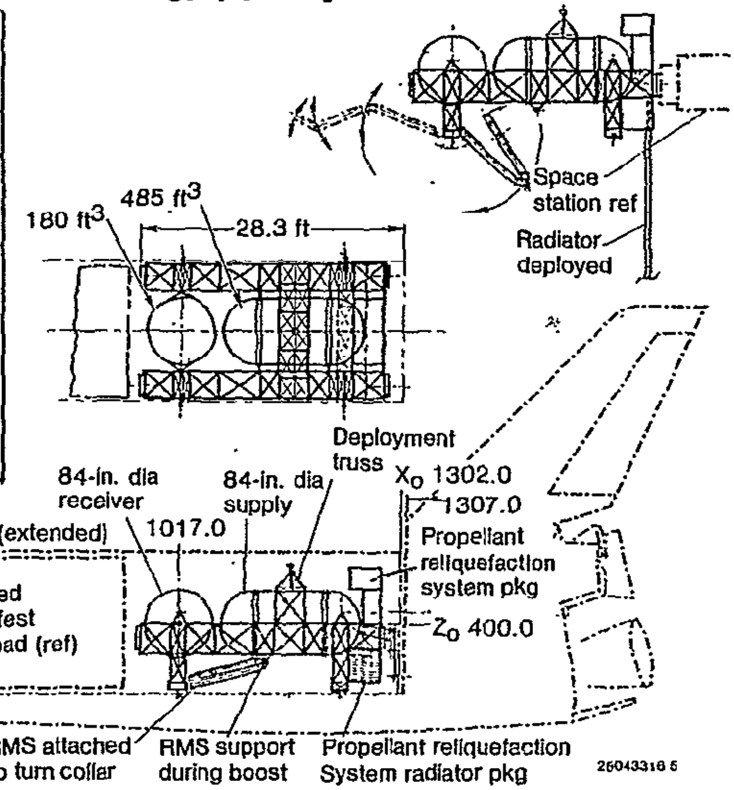

Figure 3-9 Propellant Transfer, Storage & Reliquefaction TDM

supported from the truss structure which, in turn, interfaces with the shuttle longeron and keel fittings. The support truss also has berthing systems on the forward and aft ends, and a bridge structure equipped with a fitting for attaching to an RMS. The aft end attaches to the Space Station and the forward end attaches to a second TDM delivered on a subsequent flight. The refrigeration unit is supported from the aft ends of the trusses and includes a deployable radiator package.

The open truss support structure has two truss yokes (one forward and one aft) which interface with the Shuttle support fittings. The forward yoke is equipped with a swivel collar, which in turn supports a RMS. The RMS is for OTV servicing and berthing operations, and is shown in the stowed position.

3.3 END-TO-END MISSION OPERATIONS

The operations to perform this TDM are now described, including the attachment of the TDM to the Space Station after being unloaded from the Shuttle. The number of crewmen for both the IVA and EVA operations are identified, and the support equipment required to perform the operations and whether it is located on the TDM or on the Space Station are also identified.

3.3.1 TDM OPERATIONS. The ground rules for the operations tasks and the approach to identifying the operations was described in Section 2.3.2. A functional flow of the TDM operation is described here, along with the timelines and number of crewmen required.

3.3.1.1 Functional Analysis. Figure 3-10 is an example of the functional/operational flow diagram we have generated for this TDM. The operations start with the docking of the orbiter to the station, and go through the unloading of the TDM equipment, the attachment of the equipment to the station and its check-out, and the performance of the TDM activities.

3.3.1.2 Timelines. Figure 3-11 is the timeline we generated for this TDM. The timeline covers the functions identified in the previous figure.

We analyzed how to perform the functions in space, and whether they should be mechanized or performed by the crew doing EVA or IVA, and what support equipment was required. We called upon our experience with cryogenic upper stages on the ground, as a starting point, to analyze and select the way a task should be done in space. This is illustrated under the discussion on the Maintenance TDM (Section 5.3). In addition, our subcontractor, Hamilton Standard, assisted us in defining times for the EVA/IVA tasks.

It takes the first day after the orbiter docks to unload the TDM and attach it to the Space Station. The type of equipment and crew activities (IVA and/or EVA) are identified along with the task times. The same kind of data was generated for the other days of activity to perform this TDM.

Figure 3-12 presents the summary timeline for this TDM from the timelines shown on the previous figure. This figure shows the tasks and timelines, the number of crew, and whether the tasks require EVA or can be done IVA.

The timelines shown on the first page cover the first five days of operation. The first day involves extracting the TDM from the Shuttle and attaching it to the station. The second day is used to integrate the TDM with the station and check it out. We have allowed three more days after the TDM has been checked out for system stabilization (outgassing). It has been our experience that this time is needed to reach true equilibrium. Very little crew time is required during this time for this operation. They can be used to perform other Space Station activities.

The continuation of Figure 3-12 shows the operations and timelines required to perform the propellant transfer and storage tests on day 6 and initiate the reliquefaction tests on day 7.

The transfer tests can be controlled from inside the space station with the number of crewmen shown. Several tests will be run during that day's testing period and the conditions and parameters monitored.

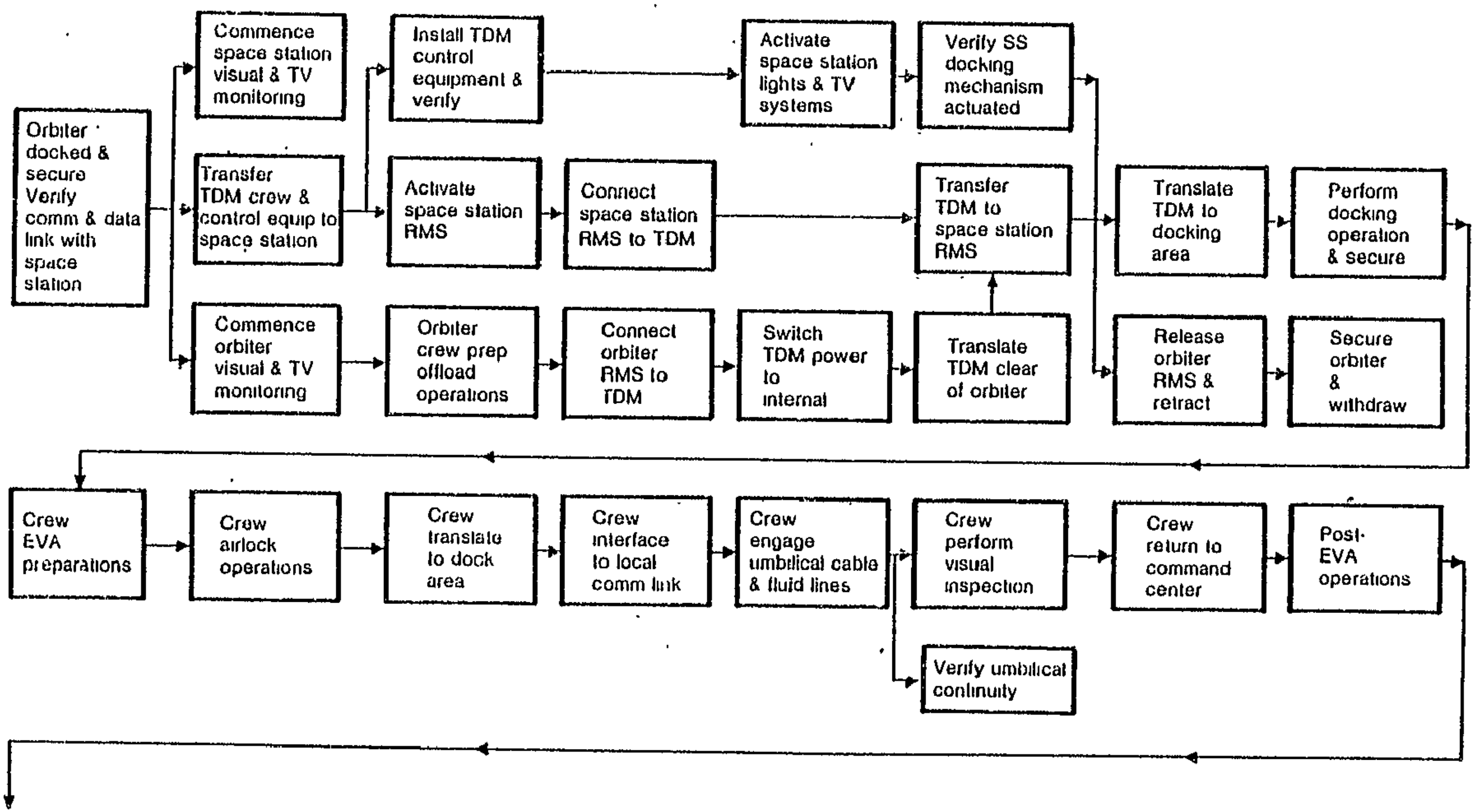

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Figure 3-10 Propellant Transfer & Storage TDM Operations

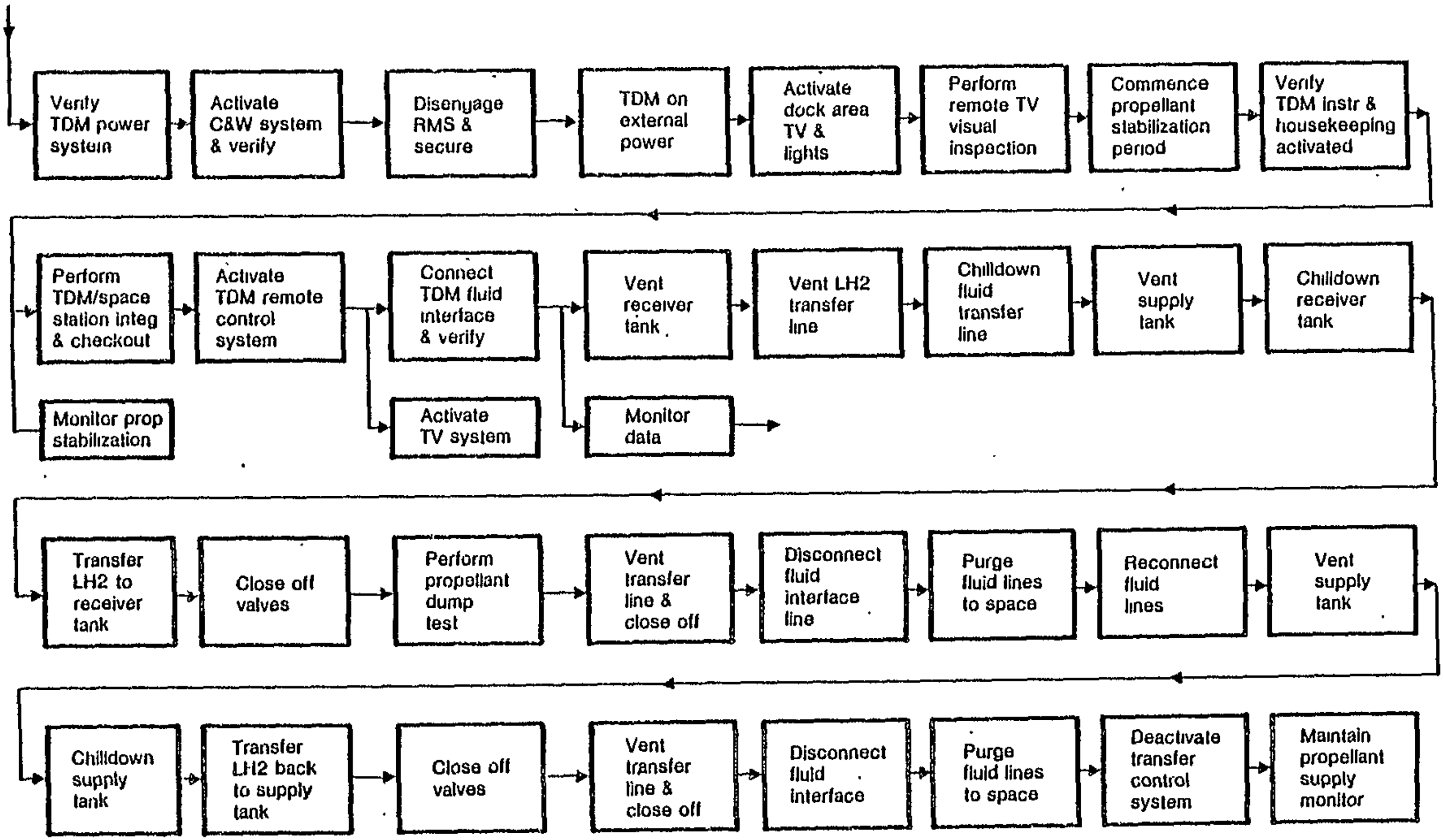

Figure 3-10 Propellant Transfer & Storage TDM Operations (cont)

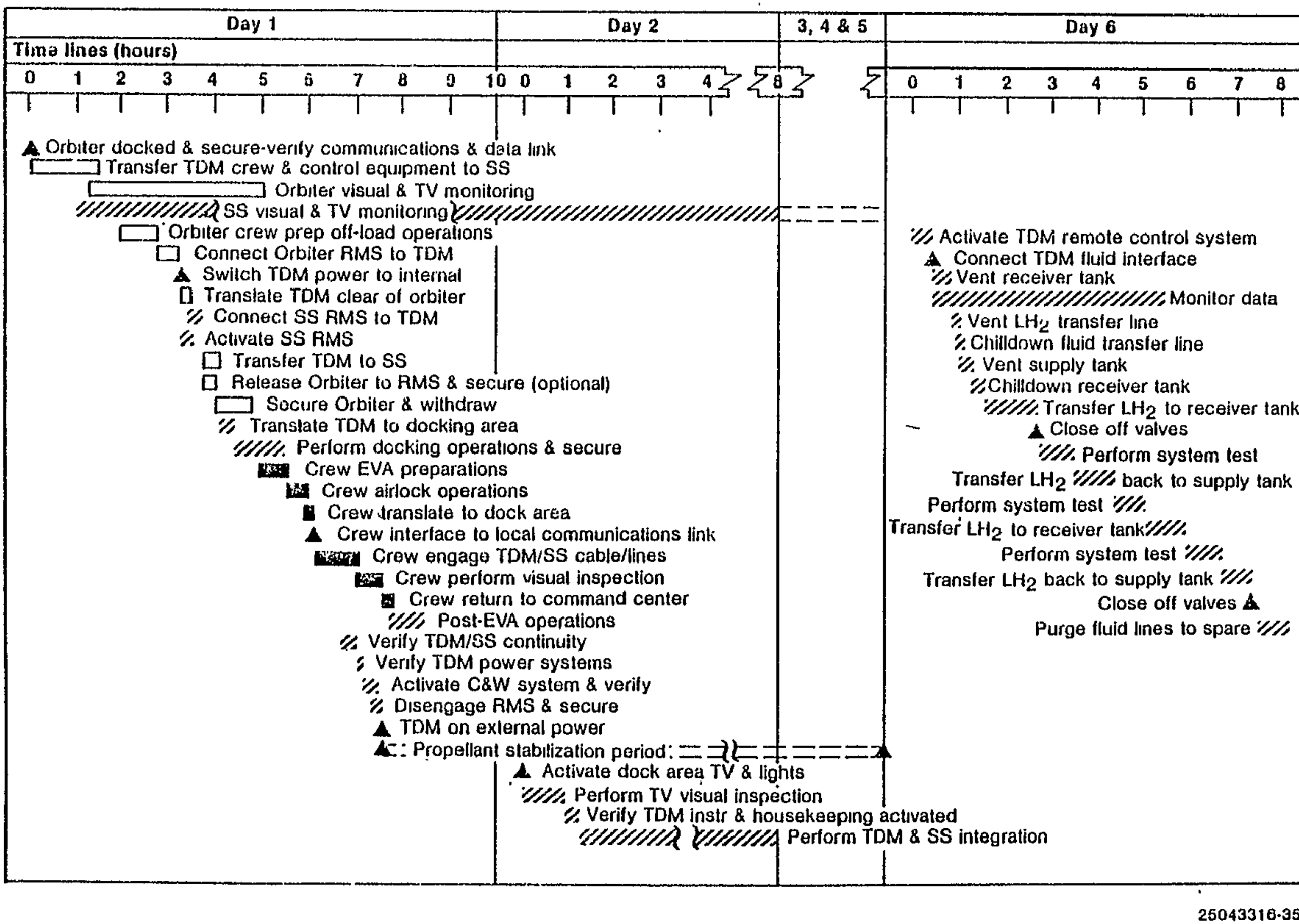

Figure 3-11 Propellant Transfer & Storage TDM Operations

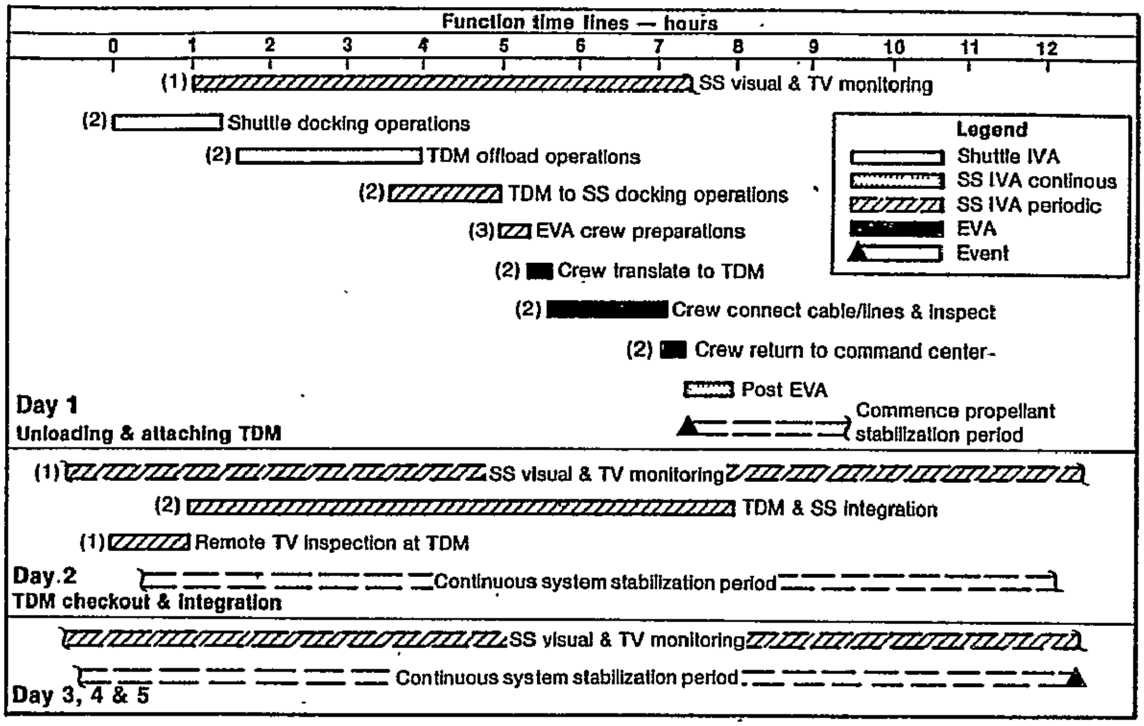

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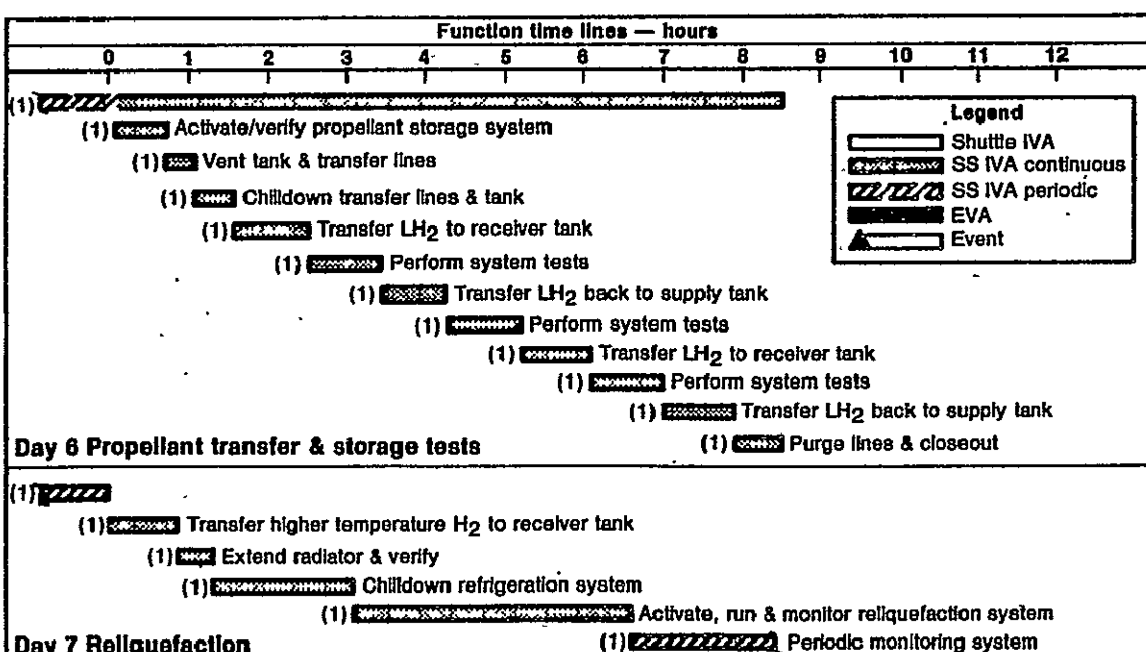
Figure 3-12 Propellant Transfer & Storage TDM Operations



Note: LH_2 transfer & monitoring operations shown should be repeated ≈5 times under varying temperature/pressure, flow rate, etc. conditions to obtain the desired data base

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Figure 3-12 Propellant Transfer & Storage TDM Operations (cont)

The LH_2 transfer operations shown should be repeated 5 times under varying conditions of temperature/pressure flow, etc. in order to cover the range of conditions to develop the desired data base.

The reliquefaction test will be initiated on day 7 and will take most of the day to get operating. Once the system is running, it will run continuously for approximately 25 days. It is more efficient to operate continuously than intermittently, so that the equipment doesn't have to be chilled down more than once.

3.3.2 SUPPORT EQUIPMENT. Figure 3-13 lists the support equipment, identified from our operations analysis, required to perform the TDM and where it is located, along with comments concerning this equipment. The next Section addresses the support/accommodations required of the Space Station by the Propellant Transfer/Conservation TDM.

3.4 SPACE STATION ACCOMMODATIONS

Interfaces, attachment approach and supporting requirements which the Space Station must provide to accommodate this TDM are presented in this section.

3.4.1 SPACE STATION/TDM INTERFACE/ATTACHMENT

3.4.1.1 Space Station RMS. If the shuttle is docked close to the first TDM berth, the TDM can be lifted from the Shuttle payload bay by the Shuttle RMS

Item	Location		Comments
	TDM	Space Station	
Remote control TV system	Cameras	Remote control panel	Some cameras may be in fixed position & focus
Lighting system	Lights & local control	Remote control panel	
EVA crew suits + EMUs	Local panels containing data link & communications interfaces	Store & recharge	Local panels wil be hardwired with datalink, communication & some emergency facilities
EVA helmet heads-up display	Local plug-in panels	Transfer units Data library	SS will transmit engineering data & planning direct to heads-up display
Remote manipulating system arm	On TDM structure	Remote control panel	Will be used for future TDM buildup & servicing
Power, communication, data link & TV electronic interfaces	(1) TDM to SS (2) TDM to TDM	SS to TDM	Connectors must be capable of remote-guided auto mating & securing
Elect hardwiring	TDM to TDM interface	SS to TDM interface	Inter-TDM hardwiring to include docking & berthing hardwire requirements
Cherry picker/transport rails	On TDM structure rails with local control	Remote control panel	Cherry picker will be used for all TDMs which will provide compatible rails installations

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Figure 3-13 Propellant Transfer/Conservation TDM Support Equipment Summary

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and placed onto the Space Station latching interfaces (see Figure 3-14). The Shuttle RMS however is not long enough for placing the second TDM onto the first TDM.

If the Shuttle is docked remote from the TDM attachments, a Space Station RMS mounted on a moving carriage will be required to extract the TDMs from the Shuttle payload bay and transport them to the TDM berthing area. Therefore we will require a translating RMS on the station to attach the TDMs.

3.4.1.2 Space Station/TDM Interface. Listed on Figure 3-15 are the interfaces between the Space Station and the Propellant Transfer/Conservation TDM. Not all of the interfaces are required to perform the propellant experiments, some are required on subsequent TDMs. However, we feel that they should be connected when the first TDM and station are brough together, rather than wait until later.

3.4.1.3 Space Station/TDM Attachment. Attachments between the first TDM and the Space Station and between the first and second TDMs must carry structural loads, have provisions for alignment, have electrical carry thru, and incorporate features for easy alignment during manipulations by the RMS. The concept shown in Figure 3-16 for the Space Station attachment uses a probe/drogue type arrangement. The two probe assemblies are attached to the Space Station structure with an adapter, and are equipped with over center screw jack driven latching panels. One probe assembly has two motor driven electrical connectors, and the second probe has provision for absorbing center to center tolerances during mating.

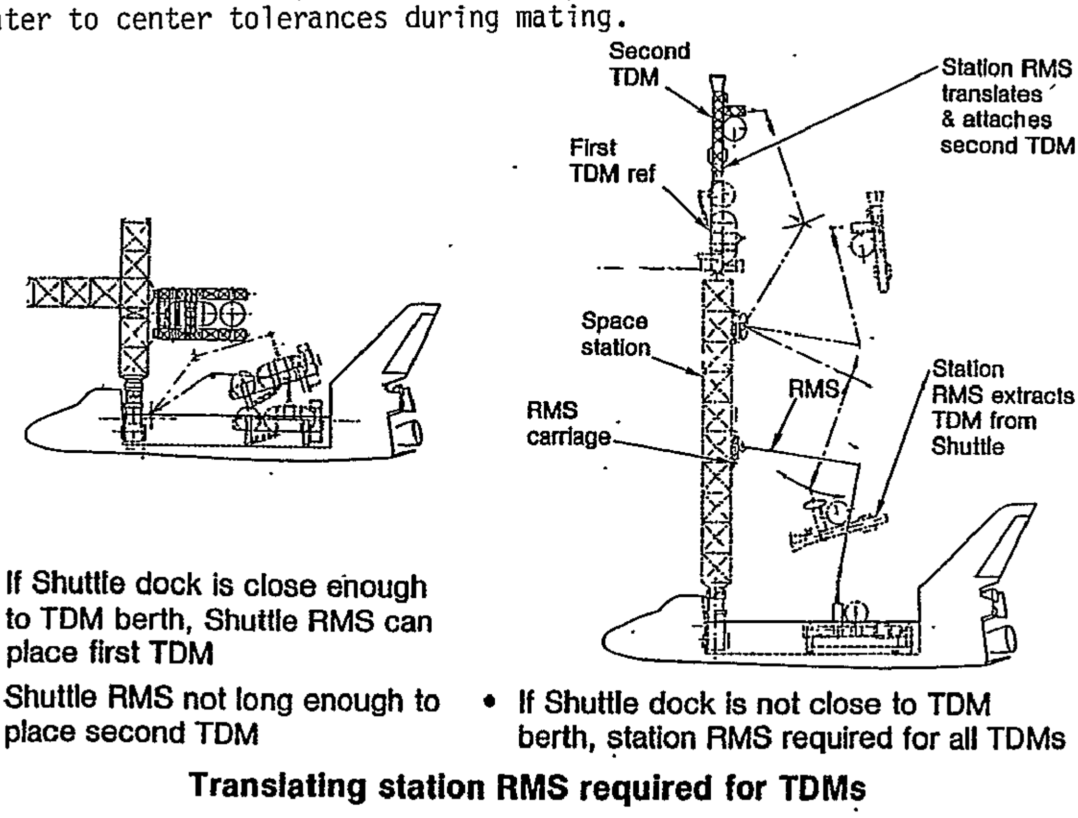

Figure 3-14 Propellant Transfer TDM Attachment to the Station

- Mechanical attachment
- Electrical power & control
- Communication lines
- Remote TV system — monitor & control
- Propellant transfer — monitoring & control system
- "Cherry picker" control
- Scissor crane control
- OTV docking, berthing & positioning control system
- Shelter translation control
- Shelter & TDM lighting — monitor & control

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Figure 3-15 Space Station - TDM Interfaces Summary

The two drogue assemblies are attached to the first TDM structure through a system of screw jack actuators and a center ball type connection to a bulkhead. One drogue assembly has two passive electrical receptacles which mate with the electrical connectors on the probe assembly. After the drogues are latched to the probes, the TDM structure is aligned by energizing the screw jack actuators.

The concept shown for the attachment between the first and second TDMs is similar to that shown for the space station attachment. The latches and electrical connectors must be arranged such that the rails for the maintenance enclosure and the personnel restraint carriages can have continuity at this connection.

3.4.2 <u>SPACE STATION SUPPORT</u>. Figure 3-17 identifies the total Space Station support for this TDM. The Space Station interfaces and some of the equipment have been identified in previous figures. The expected power required is shown with a requirement of approximately 500 watts continuous during the 25 days the reliquefaction system is operating. The 400 watts for the transfer experiment is required only during the running of the test. About 40 ft^3 of volume will be required for the controls and displays for the Space Station RMS and the tests. Two EVA suits and EMUs will be required. Ground communications will be required for any additional consultation during the tests. A low g environment (L1 x 10^{-5}g) is required for testing acquisition and zero-g gauging systems. The skills and levels for the three crewmen are indicated. The skill type and skill level definition are from the payload element description instructions for the Space Station.

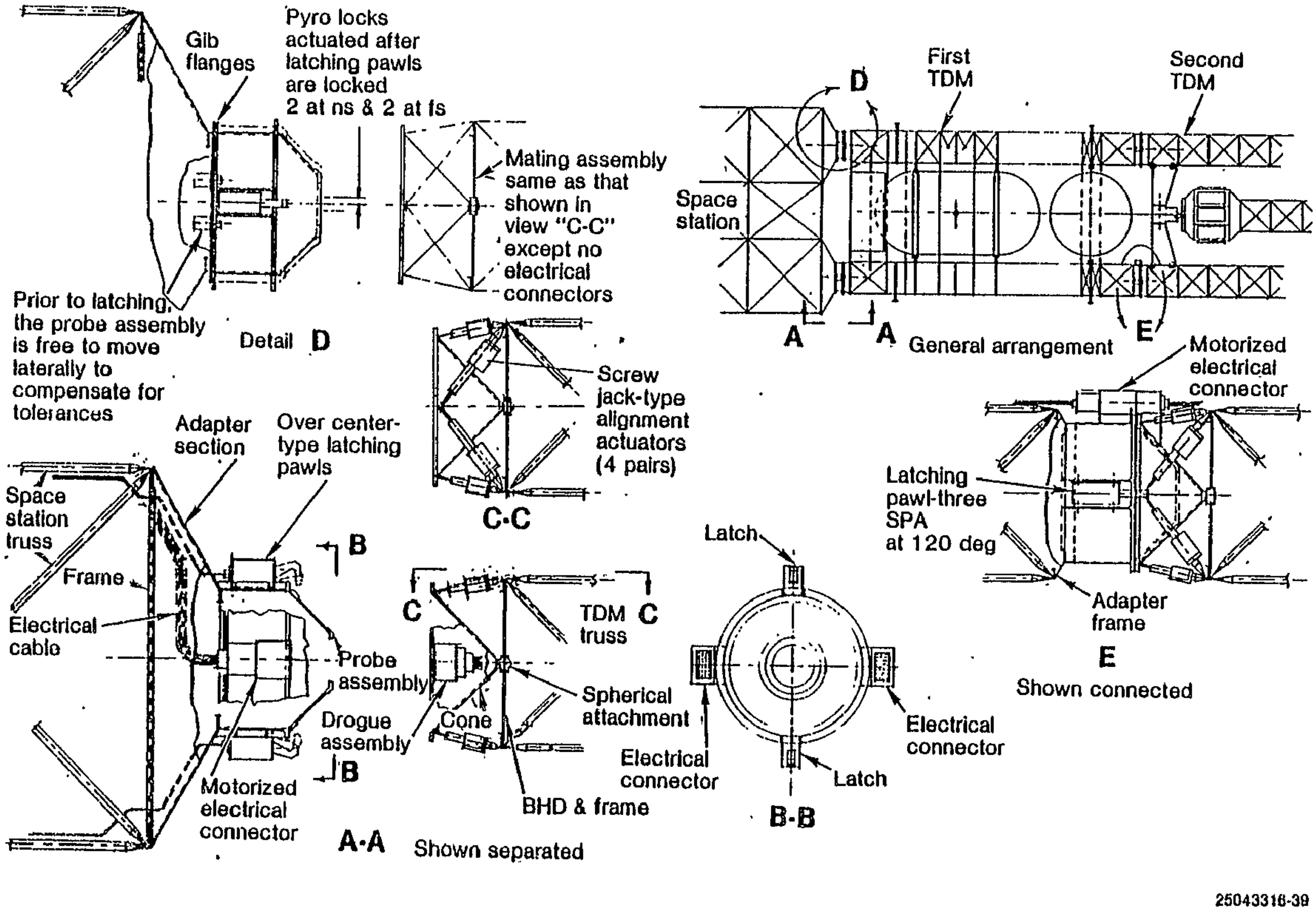

Figure 3-16 Space Station/TDM Attachment

- Translating RMS & control station
- Mechanical attachment & power, controls, data, communications, TV interfaces
- Power — 500 watts continuous (reliquefaction & monitoring)
  400 watts during transfer experiment
- Data acquisition & processing, remote TV & caution & warning systems
- Communication — ground & TDM (RF & hard line)
- Volume ≈ 60 ft^3 for controls & displays plus cooling system
- 2 EVA suits, helmet heads-up displays & EMUs plus storage & cleaning facilities
- Astronaut egress, ingress & translation system to TDM
- Low-g environment required for testing acquisition & zero-g gauging systems
- Crew skills: One spacecraft systems professional (skill 7, level 3)
  Two engineering technicians (skill 5, level 2)

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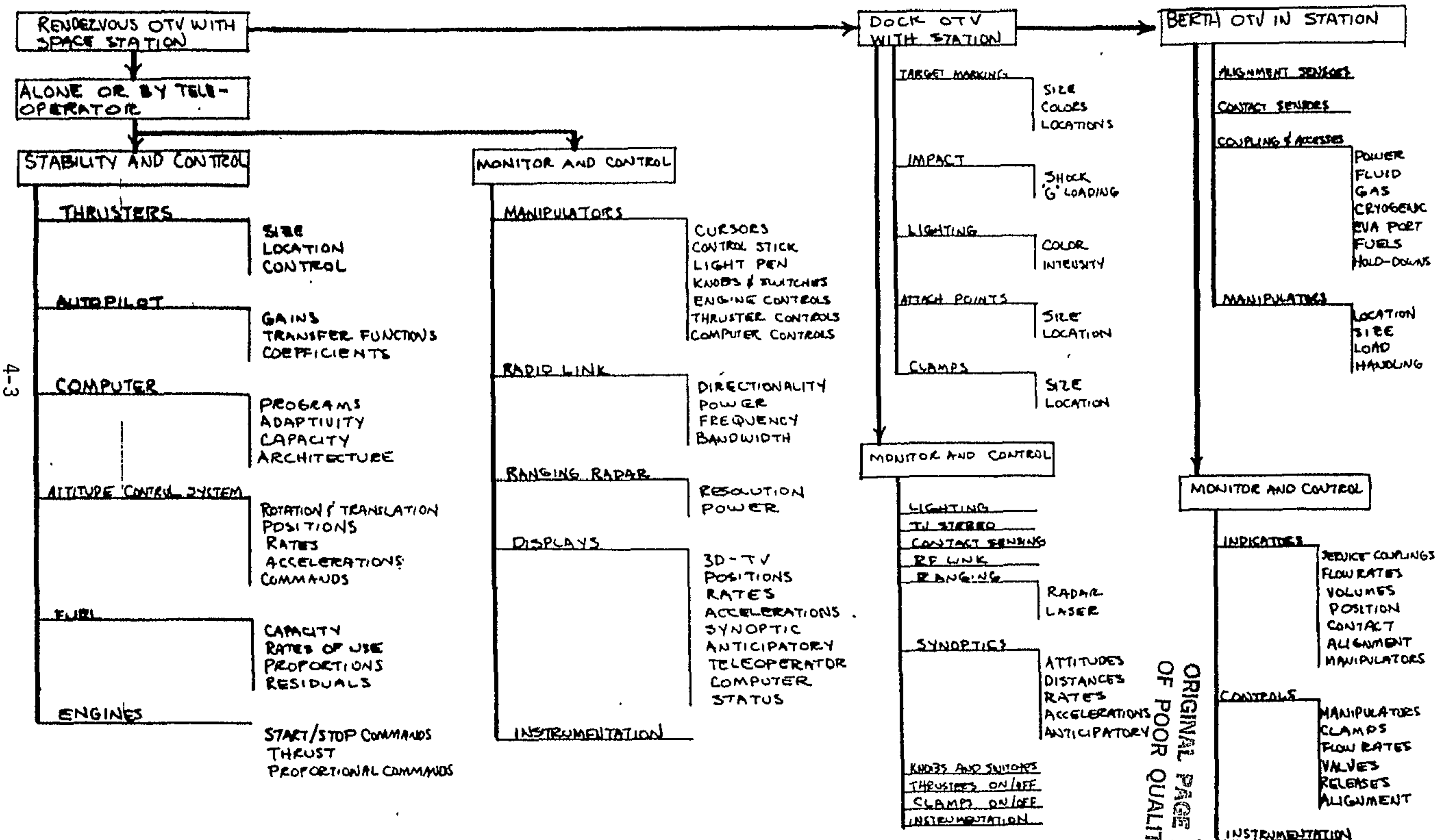
Figure 3-17 Propellant Transfer TDM Space Station Support



e 4-2 OTV Rendezvous and Docking

Function	Development Tests			Rationale for Space Station Level Test
	Ground	Shuttle Sortie	Space Station	
Docks OTV with space station				
• Stability & control system	X	X	X	• Ground checkout tests of all the system components & system. In addition, a ground simulator is required • Shuttle sortie tests using a TMS to simulate OTV • Verify docking operation on & around a space station configuration both for the hardware & the procedures. Check out automated & manual backup
Thruster size	X			
Thruster location(s)	X			
Autopilot gains	X			
Autopilot trans function	X			
Autopilot coefficients	X			
Computer programs	X			
Computer adaptivity				
Computer capacity	X			
Computer architecture	X			
ACS rotation	X			
ACS translation	X			

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Figure 4-4 OTV Docking Development Tests Matrix

Function	Development Tests			Rationale for Space Station Level Test
	Ground	Shuttle Sortie	Space Station	
ACS position	X			
ACS rates	X			
ACS accelerations	X			
ACS commands	X			
Fuel capacities	X			
Fuel use rates	X			
Fuel proportions	X			
Fuel residuals				
Engine start/stop	X			
Engine thrust	X			
Engine steering				
• Monitor & control system	X	X	X	
Cursors	X			
Control stick	X			
Light pen	X			
Knobs & switches	X			
Engine controls	X			
Thruster controls	X			
Computer controls	X			

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Figure 4-4 OTV Docking Development Tests Matrix (Cont'd)

4.0 DOCKING AND BERTHING TECHNOLOGY DEVELOPMENT MISSION

This section defines the selected Docking and Berthing TDM. The definition was generated by performing the tasks as described in Section 2.0 including iterations. The final definition is presented here with some discussions of the iterations performed.

The TDM definition encompasses 1) the mission requirements including a description of the evolutionary technology development plan with emphasis on the tests to be performed at the initial Space Station, the TDM mission objectives, and mission requirements, 2) the conceptual design, 3) the end-to-end operations and support equipment requirements, and 4) the accommodations required from the early Space Station.

4.1 MISSION REQUIREMENTS

The functional analysis of OTV rendezvous, docking and berthing functions is presented to identify the areas for technology development consideration. Development test matrices are shown indicating what tests should be performed on the ground, in a Shuttle sortie mission and on the initial Space Station. The rationale for the Space Station tests is identified. Following this, the objectives and requirements for the Space Station tests are shown. These requirements drive the conceptual design.

4.1.1 FUNCTIONS. Figure 4-1 presents a summary of the low level functions which need to be performed in the rendezvous, docking and berthing operations at a Space Station to service an operational OTV. Figure 4-2 presents a further breakdown of these functions which must be considered in the development of this capability.

4.1.2 EVOLUTIONARY TECHNOLOGY PLAN. The following subsections discuss the evolutionary technology plan for rendezvous, docking and berthing.

4.1.2.1 Rendezvous. Figure 4-3 shows the testing levels proposed for the rendezvous function. We don't believe that tests need to be performed on a Shuttle sortie mission or on the Space Station. The development of this capability should be able to be accomplished satisfactorily through simulation on the ground.

4.1.2.2 Docking. Figure 4-4 is an evolutionary technology development plan matrix which identifies the testing levels proposed for the docking function. It is proposed that appropriate tests be performed on the ground, on a Shuttle sortie mission and at the Space Station.

Ground development tests of all the system components and system are required. In addition a ground simulator is required. Shuttle sortie tests using a TMS to simulate the OTV should be performed to verify zero-g capability.

A Space Station development test should be accomplished to verify the capability to perform the docking operation on and around a Space Station configuration both for the hardware and software. The capability to perform automated docking with manual back-up should be tested.

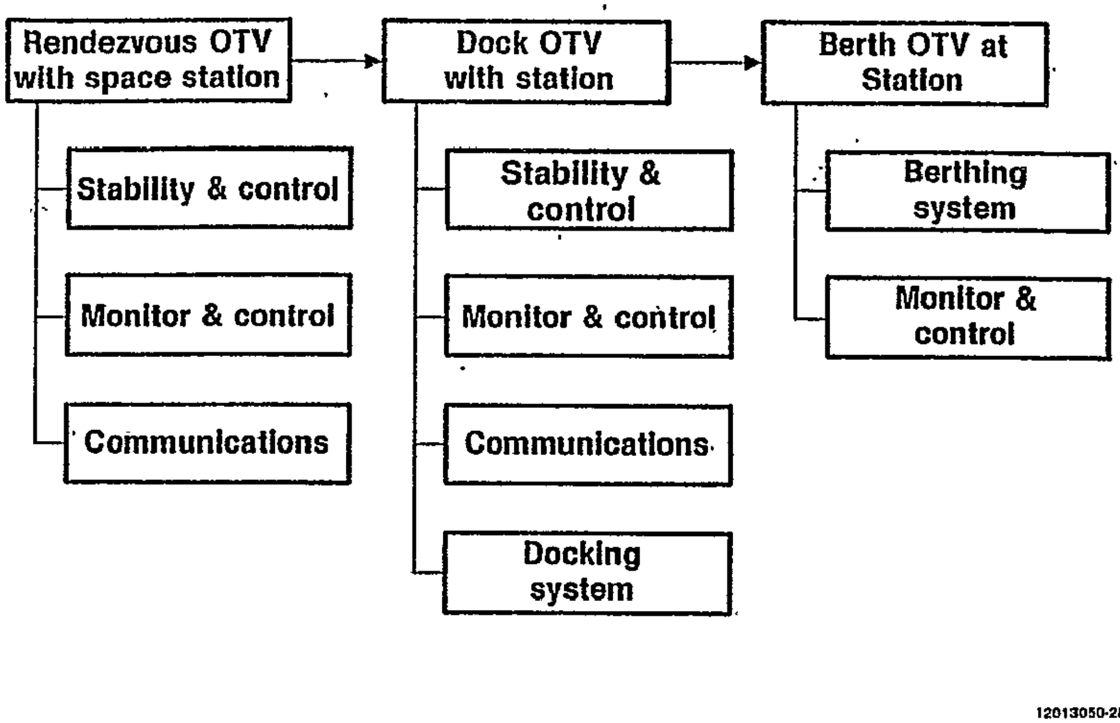

Figure 4-1 OTV Rendezvous, Docking & Berthing Functions

Function	Development Tests			Rationale for Space Station Level Test
	Ground	Shuttle	Station	
Stability & control	X			No space station tests required for the rendezvous function
Monitor & control	X			These tests should be able to be performed satisfactorily through simulation on the ground
Communications	X			

Figure 4-3 OTV Rendezvous Development Test Matrix

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Function	Development Tests			Rationale for Space Station Level Test
	Ground	Shuttle Sortie	Space Station	
• Communications	X	X	X	
Directionality	X			
Power	X			
Frequencies	X			
Bandwidth	X			
Resolution	X			
3D-TV	X			
Positions	X			
Rates	X			
Accelerations	X			
Synoptic	X			
Anticipatory	X			
Computer	X			
Status	X			
Instrumentation	X			
• Docking system	X	X	X	
Target machining	X			
Impact	X			
Lighting	X			
Attach points	X			
Retainers	X			

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Figure 4-4 OTV Docking Development Tests Matrix (Cont'd)

4.1.2.3 Berthing. Figure 4-5 is an evolutionary technology development plan matrix for the berthing function. Ground development tests of all the system components and system are required. Shuttle sortie tests are proposed for zero leak fluid disconnects.

A Space Station development test should be accomplished to verify the berthing hardware and procedures on a Space Station configuration.

4.1.3 TDM OBJECTIVES. Figure 4-6, 4-7 and 4-8 identify the objectives for the proposed initial Space Station tests for the docking and berthing functions.

4.1.4 TDM REQUIREMENTS. Figure 4-9 is a summary of the requirements for the docking and berthing TDM. These requirements were derived from the detailed descriptions of the TDM objectives presented in the previous section.

The TDM objectives and requirements were used to drive the approach and conceptual design described in the next section.

4.2 CONCEPTUAL DESIGN

The recommended TDM conceptual design is presented along with a preliminary weight statement. The docking and berthing operational sequences are described along with an alternative docking operation.

Function	Development Tests			Rationale for Space Station Level Test
	Ground	Shuttle Sortie	Space Station	
•Berthing system	X		X	• Ground checkout tests of all the system components & system
Alignment sensors	X			
Contact sensors	X			
Coupling & access	X	X		• Shuttle sortie tests on zero-leak fluid disconnect
Manipulators	X			• Verify berthing hardware & procedures integrity on space station configuration
•Monitor & control	X		X	
Indicators	X			
Controls	X			
Instrumentation	X			

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Figure 4-5 OTV Berthing Development Tests Matrix

Function	Objectives
Stability & control system	
• Thrusters	Verify size, location & control capability of thrusters needed to maneuver OTV during docking to determine that design is adequate for range of OTV configuration envisioned
• Autopilot	Determine that analytically derived gains, transfer functions & coefficients are correct for maneuvering OTV during docking
• Computer	Confirm that software, computer sizing, speed, I/O characteristics & adaptive techniques are sufficient
• Attitude control system	Determine that design concepts are consonant with requirement of OTV docking mission with space station & a defined set of GEO payloads
• Fuel capacities	Ascertain that fuel tank volumes, valving, flow rates & controls are suitable for demands of engines & thrusters so that they propel OTV during docking maneuvers
• Engines	Ensure that engine performance matches requirements for docking mission required of OTV in terms of thrust, start/stop control, steering articulation & proportional control

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Figure 4-6 TDM Objectives - OTV Docking

Functions	Objectives
MONITOR AND CONTROL	
• Lighting	Evaluate the adequacy of lighting for TV viewing and laser ranging to reveal any flaws which would not allow the visualization of the docking.
• TV Stereo	Measure the ability of the OTV manual manipulator to use 3D TV for the docking activity and quantify the accuracy of the visual measurements as seen by the man.
• Contact Sensing	Evaluate that the placement, sensitivity and operability of the contact sensors provide sufficient information to the OTV operator to establish and maintain contact with its target.
• R. F. Link	Measure the effective power, range, stability and possible interference of the radio link between the OTV and the target.
• Ranging	The ranging system will be tested for its ability to determine maneuvering distances which are displayed to the OTV operator. The goal is to assess the capabilities of both radar and laser methods.
• Synoptic Displays	The tests on the synoptic displays will reveal the ability of the manual operator of the OTV to utilize the information thus displayed in order to affect docking with a target. The goal is to assess the capability of the attitude, distance , rate, acceleration and anticipatory displays by the operator.
• Knobs and Switches	The object of these tests is to determine the operability of the selection of knobs and switches manipulated by the OTV operator to assess his docking status and to command actions as necessary. The goal is to make certain of the adequacy of the human factor engineering
• Thruster Controls	Determine the ability of the thruster controllers as used by the OTV operator to maneuver into a dock with a target.
• Clamps Operation	Determine if the sensing and display of operating the docking clamps performs as specified.
• Instrumentation	This objective is to learn if the specified tolerances and magnitudes of the instrumentation, and the responses, tell the engineer how the docking system is performing. The goal is to obtain a baseline of data for assessment.
COMMUNICATIONS	The objectives of these tests are to measure the effectiveness of the data and control transfer link and the radar distance ranging devices used to perform an OTV docking with the space station. The goals are to determine that the directionality, power, frequencies, bandwidth and resolution meet the performance criteria specified.
DOCKING SYSTEM	
• Target Marking	Determine the adequacy of the target marking on the space station in order to affect a dock with respect to size, colors, and location.
• Impact	Assure that the design of the docking mechanisms and the shock sensitive elements of the OTV and station are able to withstand the anticipated loads when contact and clamping take place.
• Lighting	Evaluate the adequacy of lighting the target for the OTV phase and determine that both the color and intensity are sufficient for visually controlled maneuver and contact.
• Attach Points	Measure the ability of the mechanisms to affect a dock under conditions of excessive tip-off angles, high shock contacts and severe misalignments. Determine the boundaries of these values based on the size and locations of the docking mechanisms.
• Retainers	Evaluate the operation, reliability and operability of the docking clamps under abnormal conditions.

Figure 4-7 TDM Objectives - OTV Docking

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Function	Objectives
BERTHING SYSTEM	
o Alignment Sensors	Ascertain the ability of the berthing sensors to indicate adequate alignment exists between the OTV and the target.
o Contact Sensors	Determine if the sensors which indicate that all berthing contact point requirements have been met operate as designed.
o Coupling and Access	Determine that the access and coupling design meet the requirements of adequate berthing of the OTV with the target. Measure the effectiveness of the power, fluid, and hold-down interfaces between the OTV and the space station.
o Manipulators	Determine the effectiveness of the manipulators to obtain a correct berthing between the OTV and the target. Assess adequacy of the location, size, load handling, and overall handling ability of the manipulator system.
MONITOR AND CONTROL	
o Indicators	Measure the effectiveness of the displays presented to the operator of the OTV in order to accommodate the berthing of the OTV and its target. Measure the capability of the service coupling, flow rate, positions, contacts, alignment, and manipulator displays.
o Controls	Ascertain the capability of the operator to operate the OTV controls relative to berthing operations. Measure the effectiveness of the manipulator, clamp, flow rate, release and alignment controls.
o Instrumentation	Determine that the measurements required are within the tolerance, magnitude and response envelopes with the goal of establishing a data baseline for these measurements

Figure 4-8 TDM Objectives - Berthing

Function	Requirements
Stability & control system	Test required to determine that stability & control system performs as designed with respect to thrust, response, tracking accuracy, fuel consumption & attitude maintenance. Use simulated OTV software & hardware. Measure response levels
Communications	Use radio link, TV system & distance ranging equipment during docking with station. Measure errors, system noise & directivity
Docking system	Provide simulated OTV attachment hardware to assess performance. Measure actuation times, forces required for actuation/release & cock-angles. Measure sensitivity, thresholds, hysteresis & visibilities
Berthing	Berth OTV simulator to station. Determine that liquid, gas & power ports match & seal
Monitors & controls	During docking of OTV simulator with station, determine that displays, controls & safety devices function

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Figure 4-9 TDM Mission Requirements - Docking & Berthing

4.2.1 DESIGN APPROACH. In order to meet the test objectives and mission requirements described in Section 4.1, a free flying OTV test bed would have to be constructed. This would be very expensive so we looked around for an alternative approach to carrying out the Space Station development tests.

The study groundrules stated that a TMS would be available at the Space Station during the time period for this TDM. Since the TMS is a free flying vehicle, we looked at using a modified TMS as a test bed OTV to do the free flying docking tests. Our investigation indicated that the TMS can be used to meet the OTV docking development tests requirements. Figure 4-10 shows the areas where the TMS can meet the requirements directly and where the TMS can simulate the software and hardware requirements. We propose that the TMS be used for the OTV docking tests.

This is the approach that the recommended TDM conceptual design follows as described in the next section.

4.2.2 RECOMMENDED DESIGN. The docking and berthing TDM (see Figure 4-11) consists of two open truss frames, a motorized carriage, a berthing/support system, a simulated OTV and cherry picker type devices for restraining the astronauts. The OTV is attached to the carriage and the berthing system and the entire package (frames, OTV, carriage, berthing system, etc.) is deployed from the Shuttle and attached to the propellant transfer TDM module.

	Meets Requirements	TMS Can Simulate	
		Software	Hardware
Stability & Control			
Thrusters			X
Autopilot		X	X
Computer		X	X
Attitude control system		X	X
Fuel			X
Engines			X
Trackers	X		
Maneuverability			
Mass		X	
Center of gravity offsets		X	X
Aspect ratios		X	X
Lever arms		X	X
Orientation		X	
Connecting Up			
Clamps	X		
Manipulators	X		
Attach points	X		
Shock mitigation	X		
Alignment sensing			X
Contact sensing			X
Target indicators			X
Hold downs			X

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Figure 4-10 TMS Can Meet OTV Test Requirements

	Meets Requirements	TMS Can Simulate	
		Software	Hardware
Communications			
Radio link	X		
TV link*	X		
Ranging	X		
Instrumentation			X
Berthing			
Fuels			X
Power			X
Cryogenics			X
Gases			X
Fluids			X
Lighting			X
Monitor & Control			
3D television*	X		
Monitors	X		
Manual manipulators*	X		
I/O devices	X		
Warning & safety signals	X		
Status displays	X		
Anticipatory displays	X		
Mode selectors	X		
*Manual case only			

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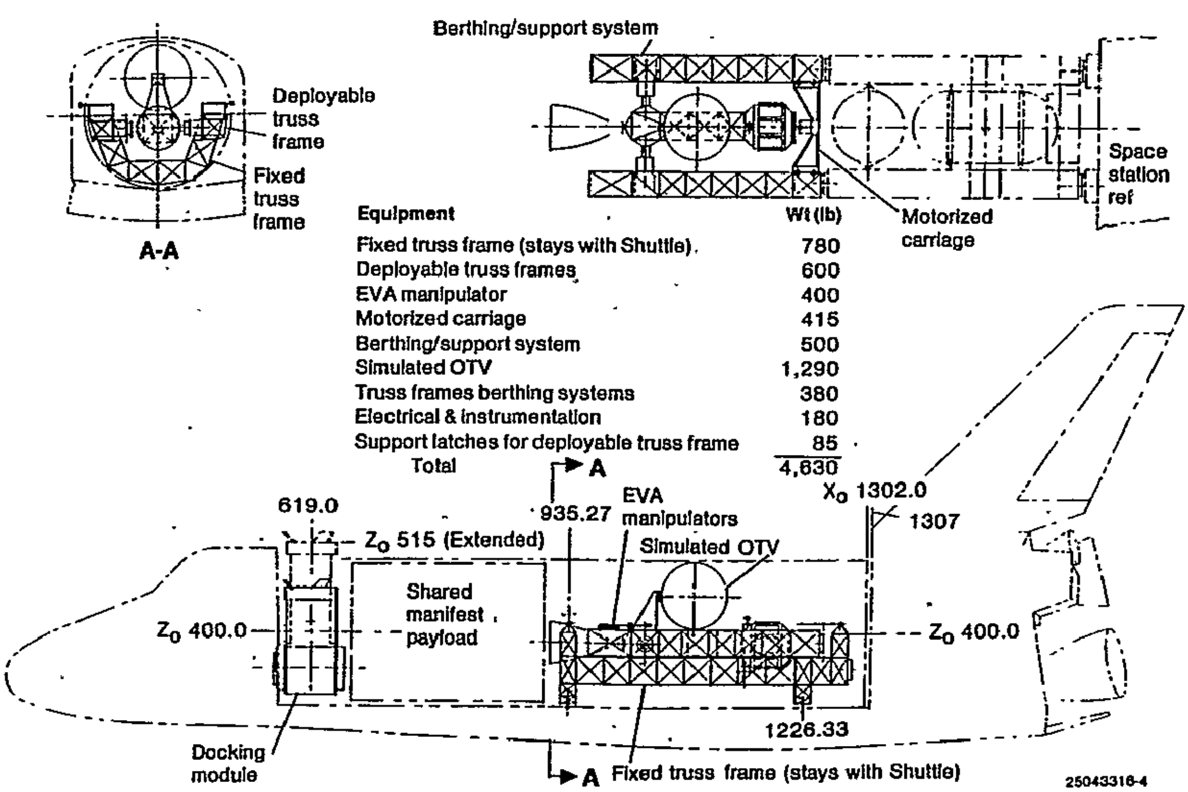
Figure 4-10 TMS Can Meet OTV Test Requirements (Cont'd)



Equipment	Wt (lb)
Fixed truss frame (stays with Shuttle)	780
Deployable truss frames	600
EVA manipulator	400
Motorized carriage	415
Berthing/support system	500
Simulated OTV	1,290
Truss frames berthing systems	380
Electrical & instrumentation	180
Support latches for deployable truss frame	85
Total	4,630

Figure 4-11 Docking & Berthing TDM

The TDM is supported in the Shuttle with an open truss yoke/frame which remains with the Shuttle. The TDM is shown in the launch configuration in the Shuttle and attached to the Propellant Transfer TDM for the orbital configuration. A Space Station RMS is used to transport the TDM from the cargo bay and attach it as described in Section 3.4.

Figure 4-12 describes the components of the simulated OTV used for the docking and berthing TDM and also for the maintenance TDM.

The modules shown can be removed from the simulated OTV for the maintenance TDM. The berthing interface is at the aft end of the core module.

The module sizes were selected to be representative of actual sizes for an OTV in order to develop the capability to handle this type of equipment in space.

4.2.3 DOCKING AND BERTHING OPERATIONS. The operational OTV must have the capability to rendezvous, dock and attach itself, carrying an unmanned or manned service module, to a satellite at GEO.

With this capability, Figure 4-13 indicates the docking scenario for an operational OTV which drives the approach for the TDM.

An OTV returning to the Space Station without a payload will be free to dock to the docking boom as shown and will be rotated, translated and engaged with the berthing components.

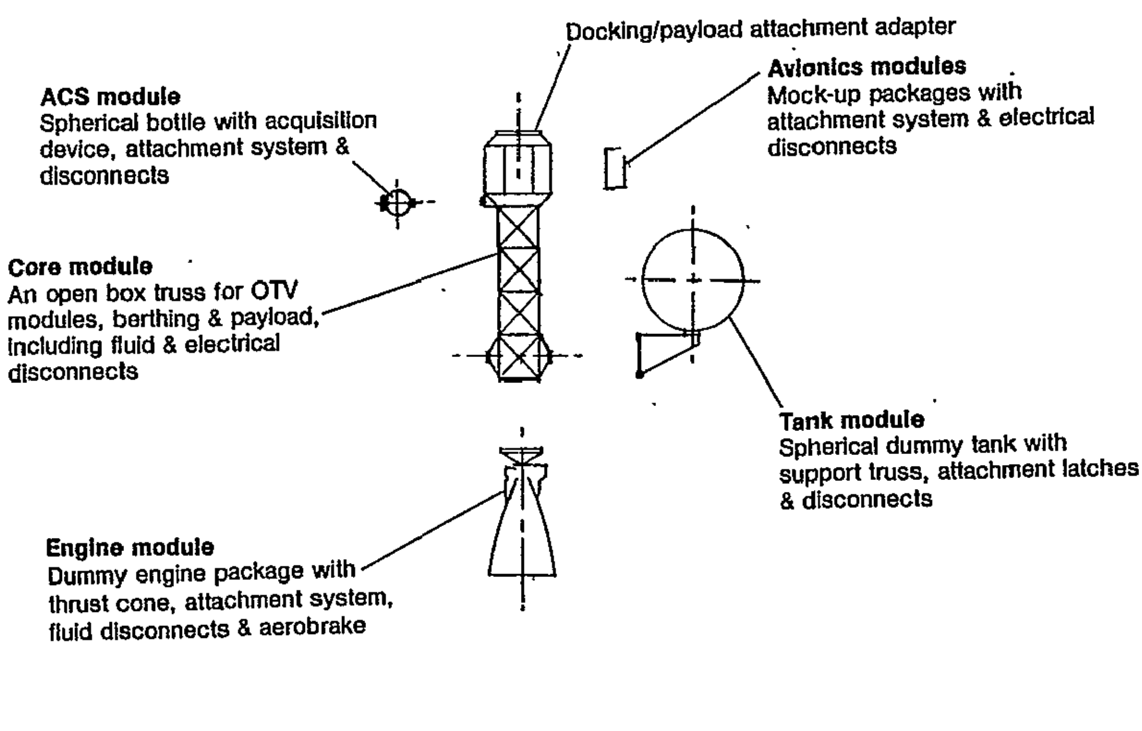


Figure 4-12 Simulated OTV

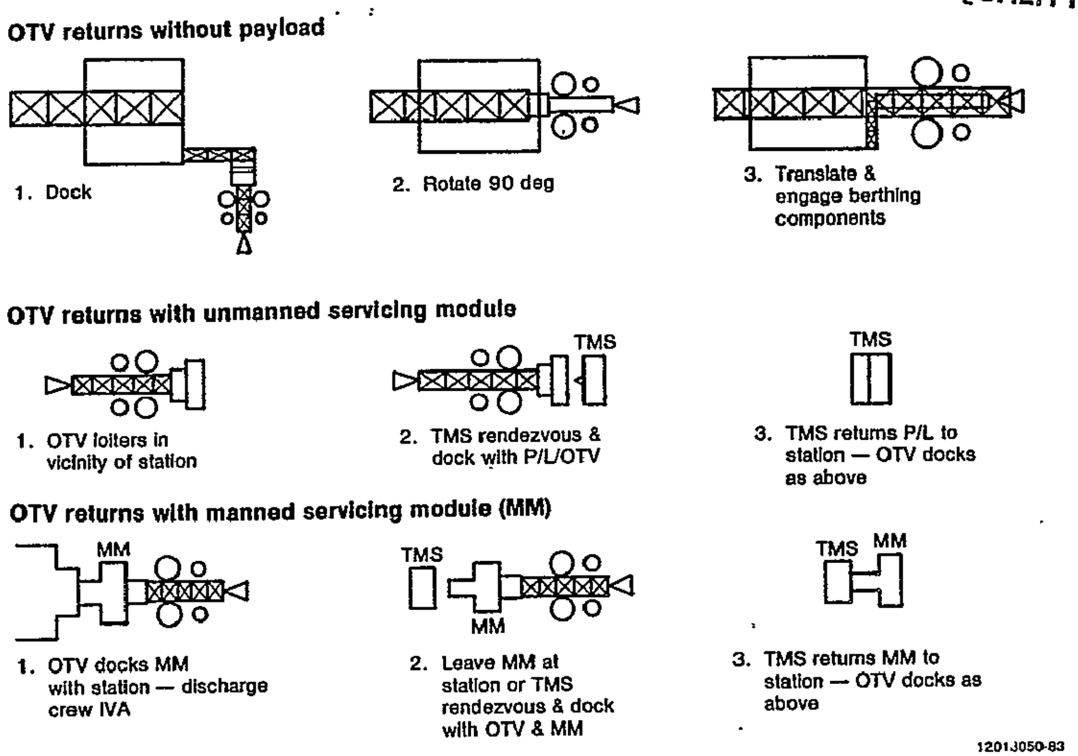


Figure 4-13 Space-Based OTV Docking Scenario

An OTV returning with an unmanned servicing module, or any unmanned payload, would first loiter in the vicinity of the station, then the TMS would rendezvous and dock with the payload/OTV, the TMS would remove the payload from the OTV and return it to the station, and the OTV would dock with the station as described above.

An OTV returning with a Manned Servicing Module (MM) would first dock the MM to the station to discharge the crew, then either leave the MM at the station or move away from the station and have the TMS rendezvous and dock with the OTV/MM. The TMS would return the MM to the station and the OTV would dock with the station as described above.

An operational OTV with a docking system would dock to the Space Station carriage as shown on the top of Figure 4-14. Since it has been established that it would be too expensive to make the simulated OTV a free flying stage, we will use a modified TMS to perform the docking tests.

The left hand picture in the middle of the chart shows the simulated OTV berthed at the station. To prepare for the docking operations, the forward end of the simulated OTV is disconnected from the carriage and the OTV is rotated 180° CCW using the berthing rotary system. We now use the forward end of the OTV as a docking target removed from adjacent structures. Docking tests are performed using a TMS equipped with an adapter.

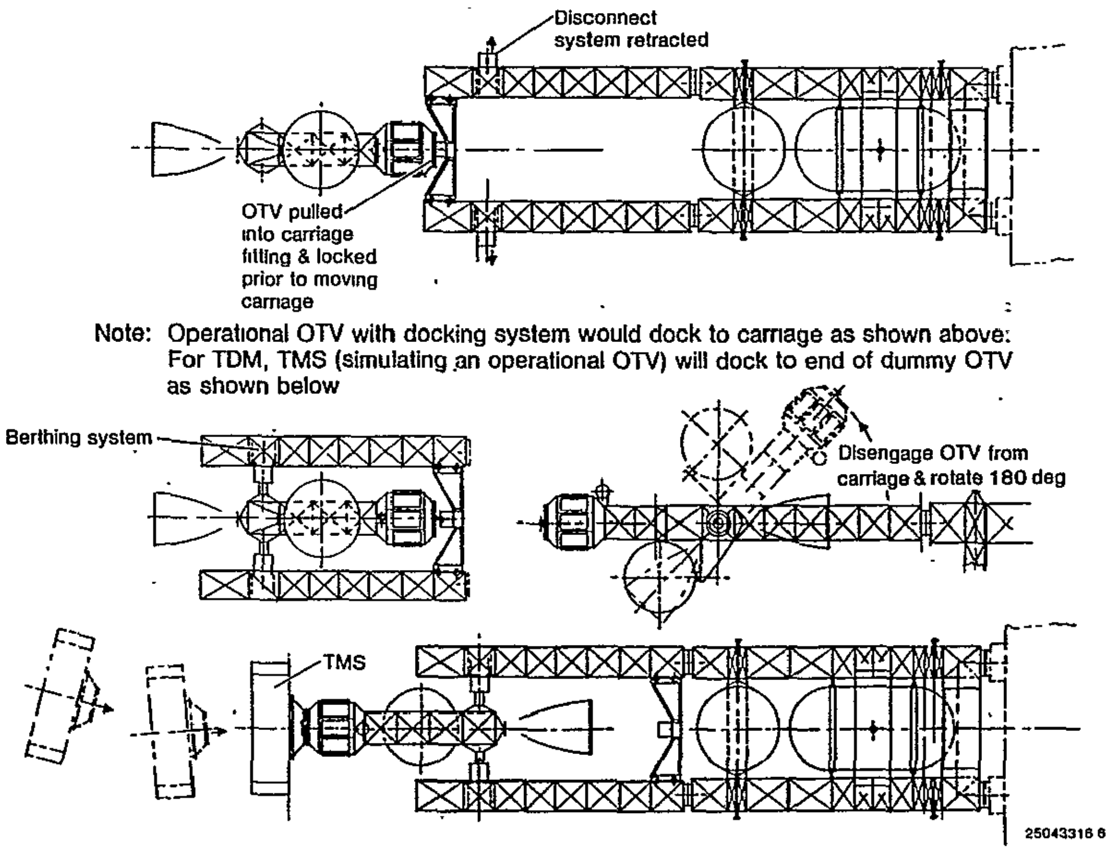


Figure 4-14 Docking Operations

For berthing operations, the OTV would start in the docking position as shown at the top of Figure 4-15. Berthing operations can be performed by moving the simulated OTV with the carriage to the right and engaging the berthing system and checking the interfaces.

4.2.4 ALTERNATIVE DOCKING OPERATION. Depending on the docking capabilities required by the operational OTV, an alternative docking method may be the selected approach. If the initial OTV doesn't require the capability to closely approach and attach itself to a satellite for the purpose of replenishing consumables and/or repair, then it may only have rendezvous capability. If this is the case, then a TMS can be used to position the OTV so that it can be picked up by the TDM RMS as shown on Figure 4-16. The RMS is then used to dock the OTV to the carriage. Using the carriage, the berthing operation can be performed as described in the previous figure.

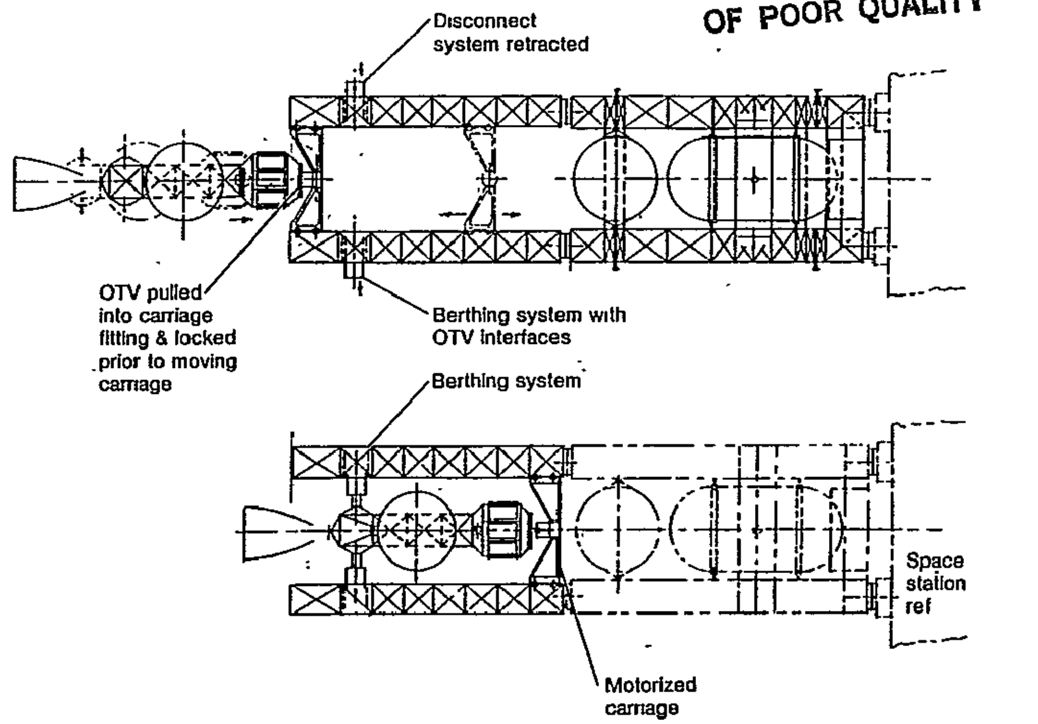


Figure 4-15 Berthing Operations

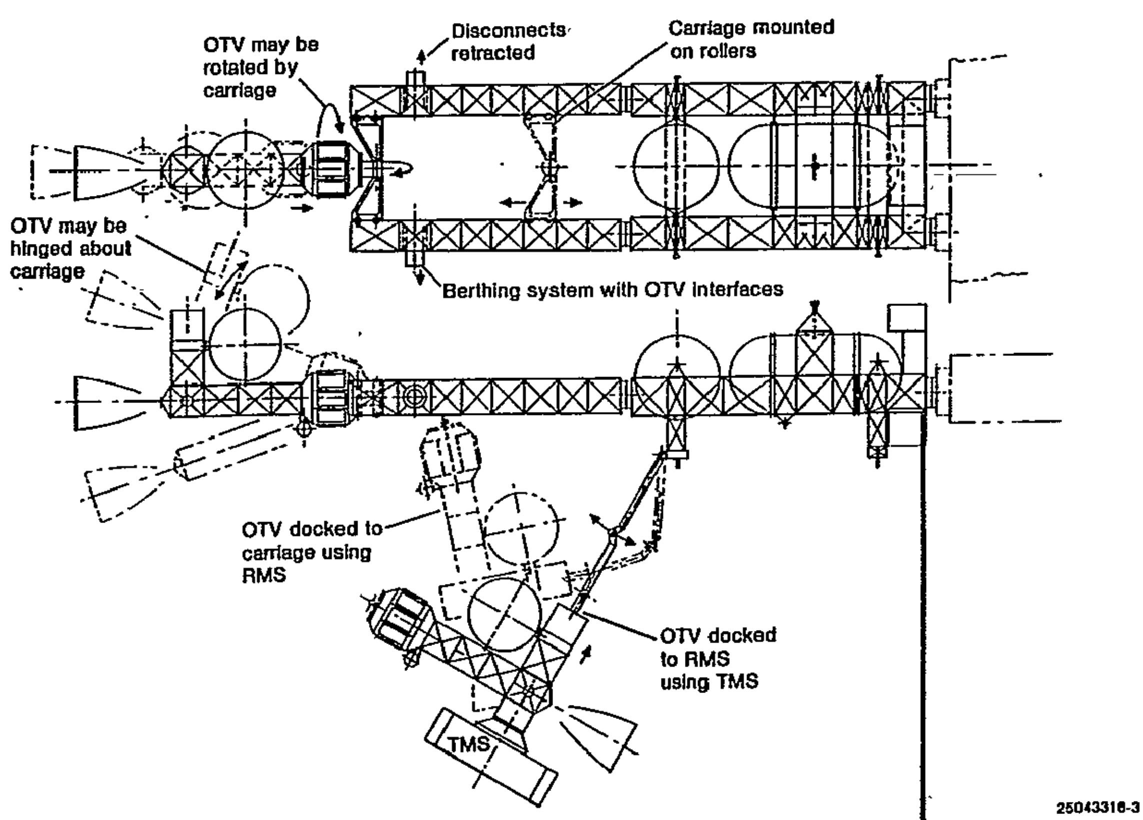


Figure 4-16 Alternative Docking Operation

4.3 END-TO-END MISSION OPERATIONS

The operations to perform this TDM are described including attaching the TDM to the Space Station after being unloaded from the Shuttle, the number of crewmen for both the IVA and EVA operations are identified, and the support equipment to perform the operations are identified and whether it is located on the TDM or on the Space Station.

4.3.1 TDM OPERATIONS.

4.3.1 TDM OPERATIONS. The groundrules for the operations tasks and the approach to identifying the operations was described in Section 2.3.2. A functional flow of the TDM operations is described here along with the timelines and number of crewmen required.

4.3.1.1 Functional Analysis. Figure 4-17 is the functional flow diagram for this TDM. The operations start with the docking of the orbiter to the station and go through the unloading of the TDM equipment, the attachment of the equipment to the station and its checkout, and the performance of the TDM activities.

4.3.1.2 Timelines. Figure 4-18 shows the timelines to cover the functions identified on the previous figure. Figure 4-19 presents a summary showing the operations and timelines required to perform the docking and berthing tests, as well as the number of crew and whether the tasks require EVA or can be done IVA.

The timelines cover the first three days of operation. The first day involves extracting the TDM from the Shuttle and attaching it to the station. The second day is used to integrate the TDM with the station and check it out. The third day is used to perform the docking tests with the TMS and simulated OTV and the berthing tests with the simulated OTV.

The docking and berthing operations shown should be repeated at least 5 times under varying conditions to obtain the desired results, and establish a good data base.

4.3.2 SUPPORT EQUIPMENT. Figure 4-20 lists the support equipment, identified from our operations analysis, required to perform the TDM and where it is located, along with comments concerning this equipment. Shown are some of the equipment required in the Space Station. The next figure lists all the support required by the Space Station.

4.4 SPACE STATION ACCOMMODATIONS

Supporting requirements which the Space Station must provide to accommodate this TDM are presented in this section. The interface between this TDM and the Propellant Transfer TDM is discussed in Section 3.4.1.

Figure 4-21 identifies the total Space Station support for this TDM. This requirement stands alone and is not additive to the Propellant Transfer TDM requirement. Except for the TMS, added controls and displays and less power, the support requirements are the same. The Space Station interfaces and some

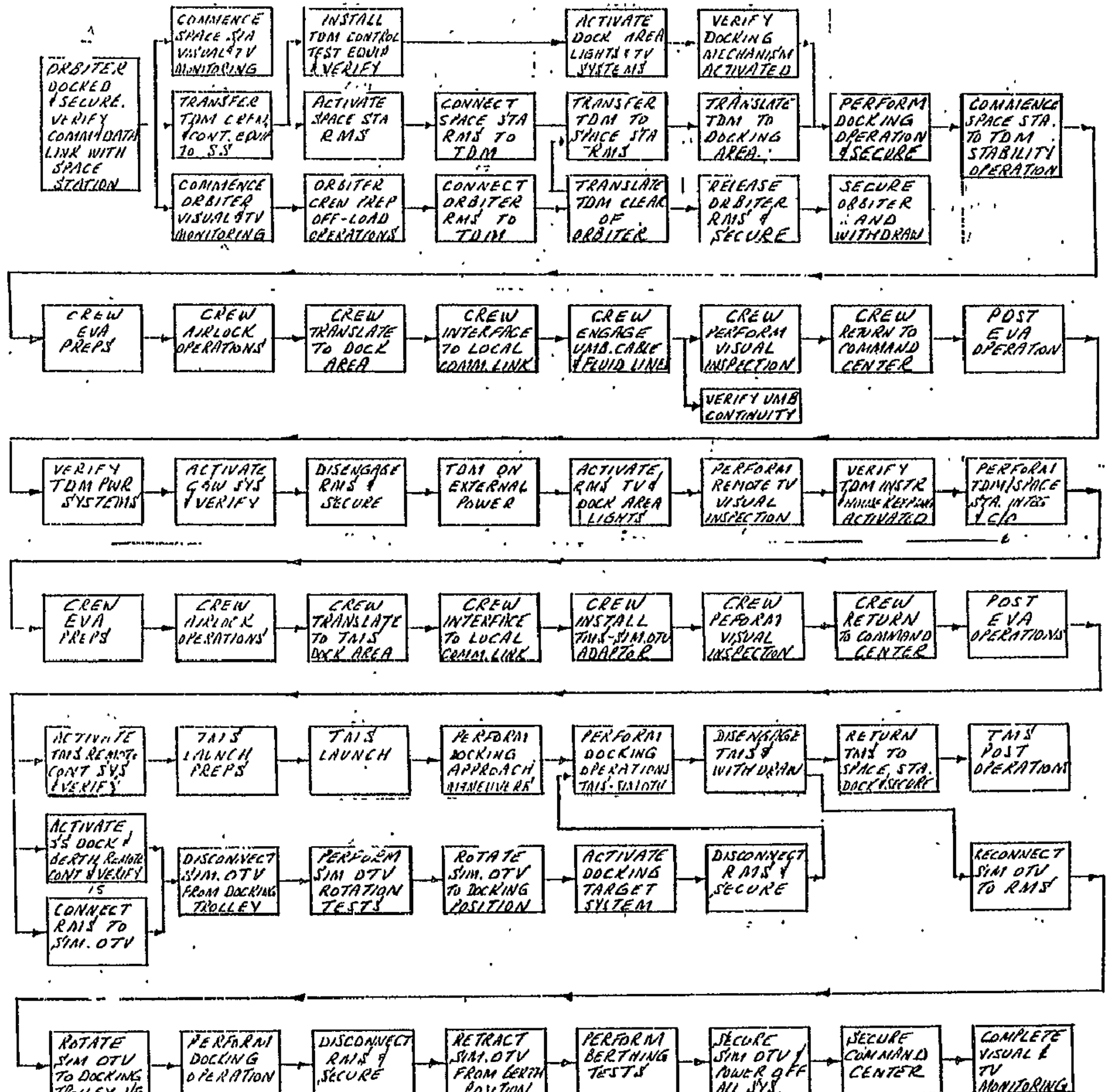


Figure 4-17 Docking & Berthing TDM Operations

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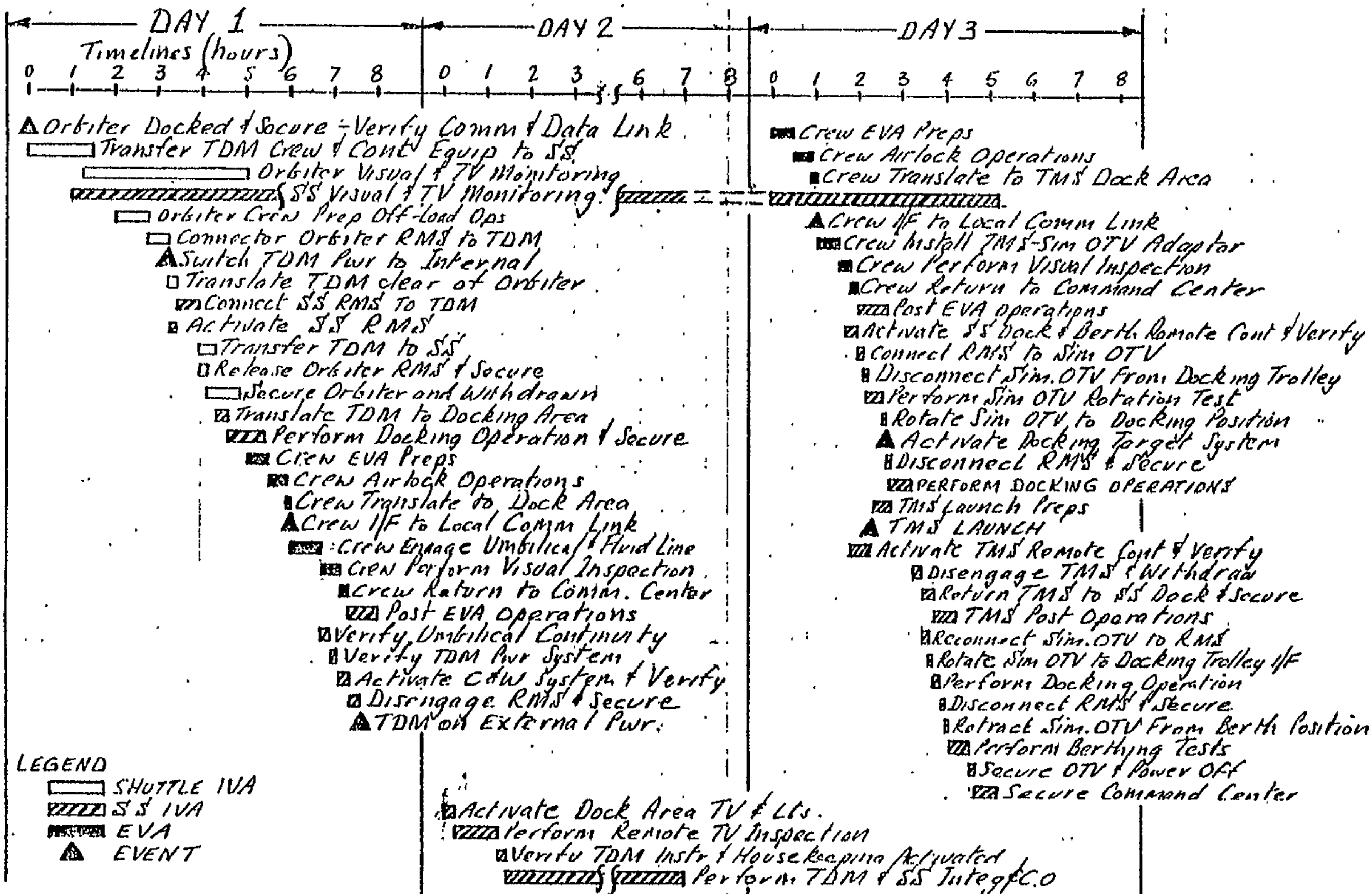
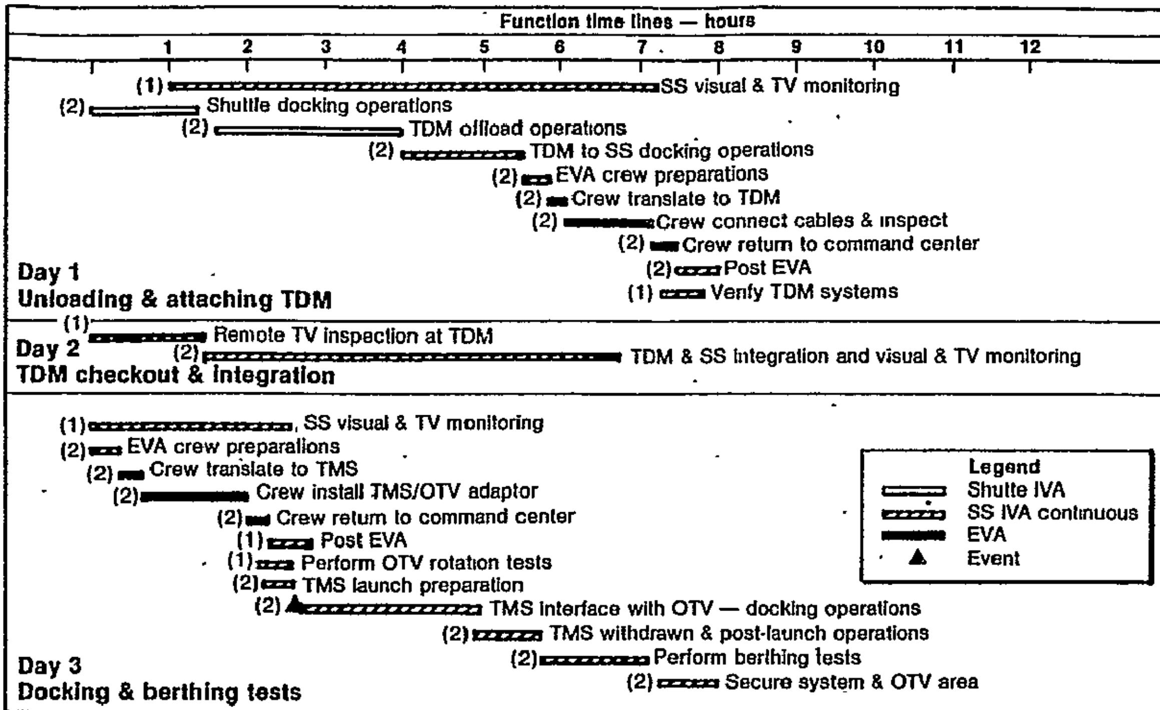


Figure 4-18 Docking & Berthing TDM Operations



Note: Docking & berthing operations shown should be repeated ≈ 5 times under varying conditions to obtain the desired data base

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Figure 4-19 Docking & Berthing TDM Operations

Item	Location		Comments
	TDM	Space Station	
Remote control TV system	Cameras	Remote control panel	Extend from propellant transfer TDM TV system
Lighting system	Lights & local control	Remote control panel	Extend from propellant transfer TDM TV system
EVA crew suits	Local panels containing data link & communications interfaces		
EVA helmet heads-up display	Local plug-in panels		
Power, communication, data link & TV electronic interfaces	TDM to TDM		To interface with propellant transfer hardwiring
Cherry picker transport rails	On TDM main truss beams	Remote control interface	
Docking carriage system	Carriage, rails & target systems	Remote position readout	Require rails full length of TDM
Berthing system	Remote interface system — mechanical & electrical	Remote readout & control	System is integrated into TDM support structure

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Figure 4-20 Docking & Berthing TDM – Support Equipment Summary

- Translating RMS & control station
- TMS plus storage provisions & control station
- Power, controls, data, communications & TV interfaces
- Power — 500W during docking & berthing experiment
- Data acquisition & processing (remote docking system with manual override), remote TV & caution & warning systems
- Communications — ground & TDM (RF & hardline)
- Volume $\approx$60 ft^3 for controls & displays plus cooling system
- 2 EVA suits, helmet heads-up displays & EMUs plus storage & cleaning facilities
- Astronaut egress, ingress & translation system to TDM
- Low-g environment required during docking experiments
- Crew skills: One spacecraft systems professional (skill 7, level 3)
  Two engineering technicians (skill 5, level 2)

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Figure 4-21 Docking & Berthing TDM Space Station Support

of the equipment have been identified in previous charts. The expected power required is shown with a requirement of approximately 500 watts during the docking and berthing tests. About 60 ft^3 of volume will be required for controls and displays for the Space Station RMS, the TMS and the tests. Two EVA suits and EMUs will be required. Ground communication will be required for any additional consultation during the tests. A low g environment is required for testing. The skills and levels for the three crewmen are indicated. These designations are from the instructions generated by NASA for the TDM forms and used in the space station payload data sheets.

5.0 MAINTENANCE TECHNOLOGY DEVELOPMENT MISSION

Maintenance operations that require concept verification and support equipment evaluation at a manned Space Station represent the maintenance TDM. The maintenance TDM is developed and presented in this section with emphasis on; maintenance TDM requirements, maintenance TDM conceptual design reflecting the required support equipment; end-to-end operations and timelines, and the accommodations required from the early Space Station.

We felt that, first, we should establish a working hypothesis based on a maintenance philosophy and operational space-based OTV and Space Station scenarios, and then derive the maintenance TDM from these operations. The significance of maintainability in our approach to defining a space-based OTV system is reflected in Figure 5-1. We constantly weighed each maintainability factor in formulating the OTV system concepts, and from these concepts we derived the maintenance operations. The basic maintenance operations were identified in Section 2.0, and now receive further definition with special attention applied to the requirements generated as a result of that effort.

During our concept definition effort, we also established that maintenance would be considered as the top level activity required to prepare or restore the space-based OTV to achieve or retain a desired operational capability. These maintenance activities or tasks were determined to include such operations as handling, assembling, servicing, repair, inspection and checkout.

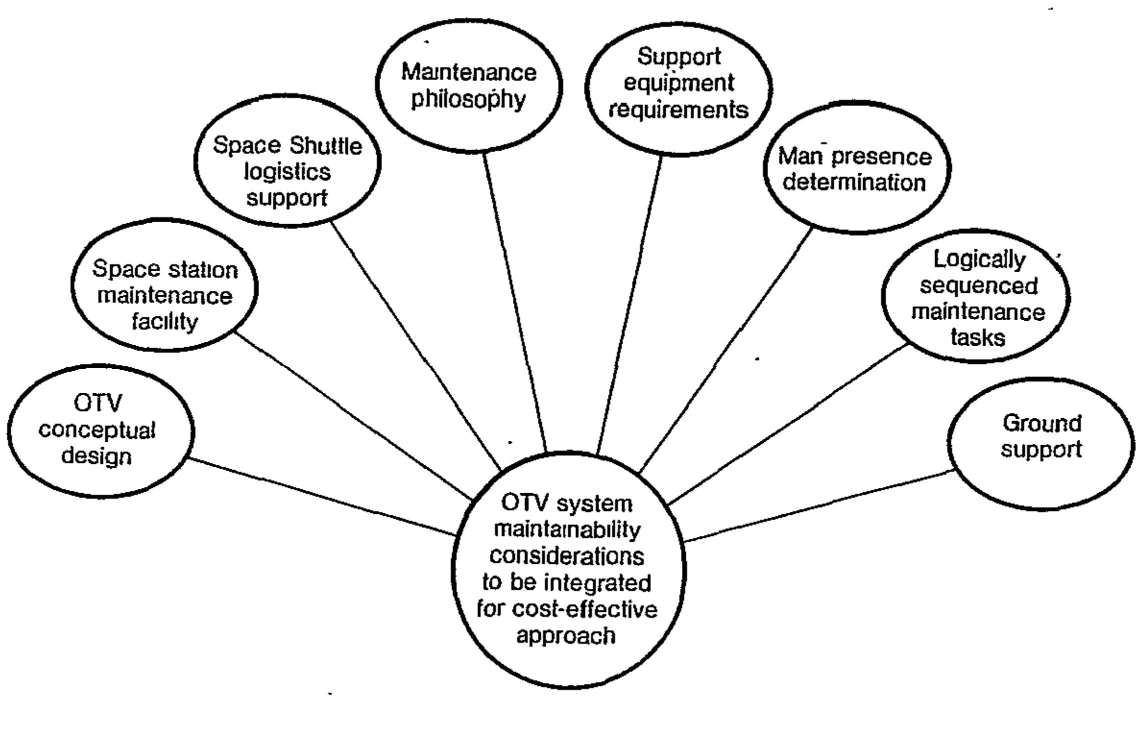

Figure 5-1 Space-Based OTV Maintainability Factors

The requirement to perform these maintenance operations in space to support a truly space-based OTV has driven the conceptual design of the vehicle. Consequently, the space-based OTV contains a high degree of desirable maintainability features. The design concept of the vehicle provides for modular construction, with plans for simplified and standardized interfaces, which allow relative ease of vehicle assembly and maintenance at a space station facility. The space station maintenance facility has also been defined to accommodate these desirable vehicle characteristics. A prevailing maintenance philosophy has evolved with the integration of the space-based OTV and the space station facility. This OTV maintenance philosophy is highlighted in Table 5-1.
The maintenance philosophy relies on a three level maintenance structure. The actual maintenance operations are further categorized as scheduled and unscheduled activities. Scheduled maintenance encompasses the entire systematic maintenance scenario including servicing and preventive actions required to retain an operational capability. These preventive actions involve inspection, failure detection and some time related remove and replace tasks, such as engine changeout. Conversely, unscheduled maintenance refers to the unplanned corrective actions required to restore the OTV to an operational level as the result of a vehicle failure.

Level I maintenance consists of the scheduled and unscheduled activities that occur on the vehicle while it is berthed in the space station maintenance dock. These Level I maintenance activities are reflected in the OTV maintenance functional flow diagram presented in Figure 5-2. A more detailed OTV retrieval and maintenance diagram is provided in the appendices. The normal OTV maintenance operations begin with receipt of the vehicle in the maintenance dock. At this point, the vehicle has been placed in the maintenance dock in a vertical position with respect to the dock structure.

Table 5-1 OTV Maintenance Philosophy

Three-level maintenance — based on level-of-repair analyses

- I OTV local maintenance
- II Space station maintenance of replaceable units
- III Return-to-earth maintenance

Stock spare parts based on reliability, criticality & cost

- Station storage vs shuttle delivery

Stress modular construction for replacement capability

Provide operational flight instrumentation & built-in test

- Fault isolate to replaceable unit

Optimize EVA vehicle maintenance operations

- Consider safety in hazardous situations
- Tradeoff EVA vs support equipment
  - — TV inspection
  - — Robotic remove & replace

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The vehicle and maintenance dock berthing interfaces are engaged and their integrity verified. The OTV is rotated 90 degrees in line with the maintenance dock and the shelter is extended to cover the OTV. Propellant leak checks are performed on the vehicle and propellant transfer system. The transfer lines undergo a chilldown process, then propellant is transferred from the vehicle to the station storage tanks. A refrigeration unit and shielding maintain the proper propellant temperatures. Visual inspection is performed on the vehicle with a television camera and monitor system. EVA inspection is limited to occur only in conjunction with some remove and replace tasks or when special damage assessment is required. While visual inspection is being accomplished, the vehicle computer-controlled fault detection system is scrutinized for fault identifications and the results are recorded for maintenance planning. Faults are verified by performing an operational test of the system. The fault is then isolated to the replaceable unit by activating the built-in test capability. Built-in test is an important feature, because it minimizes the OTV to Station interface and Station equipment diagnostic requirements. The unscheduled maintenance tasks are integrated into a complete scheduled and unscheduled maintenance plan. Some OTV components can be removed and replaced using a remotely controlled arm or a completely robotic system. The components identified as easily replaced with automatic equipment are avionics modules, ACS modules, fuel cells and batteries. Other components that may require EVA operations for remove and replace tasks are the main engine and tank modules.

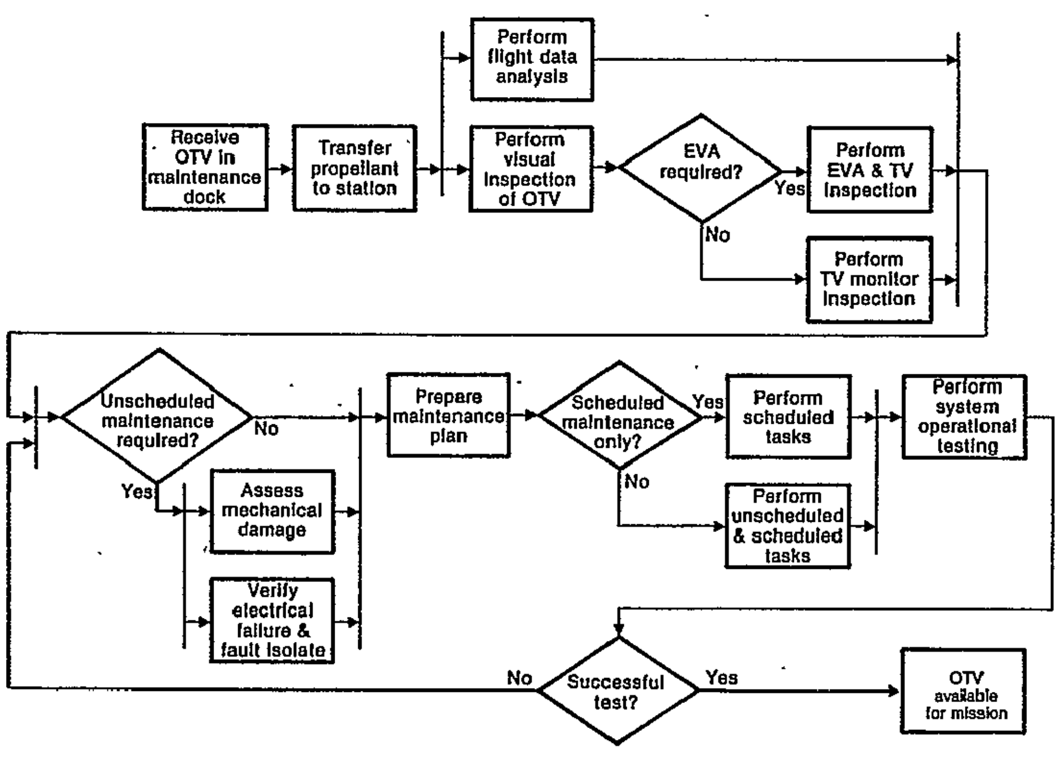

Figure 5-2 OTV Level I Maintenance Funcational Flow

With the completion of preventive and corrective maintenance activities, the vehicle receives a final operational checkout which validates that the OTV is ready for payload integration and mission operations.

The unscheduled maintenance task block in the OTV maintenance functional flow diagram Figure 5-2, has been expanded, as shown in Figure 5-3, to more clearly expose the three levels of maintenance within a corrective maintenance operation. It has been established that Level I corrective maintenance takes place on the vehicle. It is preferred that this Level I task involve remove and replace actions, but it could just as well involve some other repair activity occurring on the vehicle. A typical semi-automated remove and replace operation of an avionic module can be found in Appendix A. An EVA task is also presented in Appendix A. The Level II maintenance category encompasses the repair, or attempted repair, of removed faulty units at the Space Station. The replaceable units that fit into the Space Station maintenance facility airlock, and are determined to be free of contaminants, are repaired within the station shirtsleeve environment. Units that cannot be repaired at the station, and are transportable on the Shuttle, are returned to earth for Level III maintenance. The economic feasibility of repair on earth and return to station on Shuttle concept will be determined by an extensive level of repair analysis. Spares provisioning analyses will also identify which units should be stored at the Space Station, and which units should be delivered by Shuttle on demand. The spares analyses will be based on reliability, criticality and cost criteria.

The question of what to do with a unit that is not repairable at the station and not transportable on the Shuttle has not been answered. Future studies should address this problem.

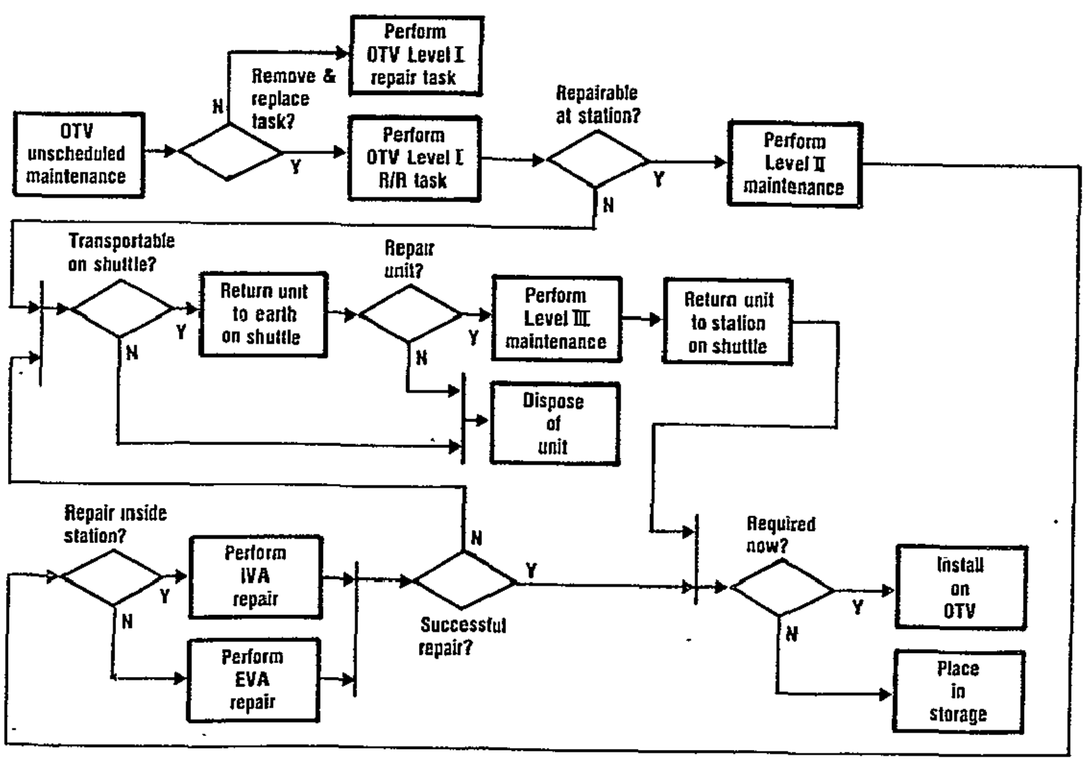

Figure 5-3 OTV Corrective Maintenance Operations

It is important to keep in mind that these maintenance operational activities and definitions were generated for an operational space-based OTV and Space Station and that maintenance TDM requirements are derived from these operations.

5.1 MAINTENANCE TDM MISSION REQUIREMENTS

The maintenance TDM requirements were formulated with the information gained as a result of conducting the space-based OTV and Space Station operational analyses. The specific maintenance development tasks to be performed on a space-based OTV were identified and are listed in Table 5.2. Servicing which is a part of maintenance is covered in Section 3.0.

The tasks were then evaluated for appropriateness as to where in the evolutionary development scheme they should occur. It was established that all tasks and associated equipment would require some development verification and evaluation at the ground segment, and that; system operation verification; unscheduled repair (other than remove and replace); and fault isolation techniques would require full development and proofing only within the ground segment. Fault detection methods could have met the same criteria for total ground based development, except for the categories of puncture and cryogenic propellant leak detection. It is felt that these detection methods should be proven in space and that experiments conducted on the Shuttle would suffice for this task equipment development. Servicing was identified for development tests in all three segment categories, but because of its status as the most important TDM, encompassing propellant storage and transfer, it has been treated as a separate TDM in Section 3.0.

Maintenance Task	Development Requirements			Rationale for Space Station Tests
	Ground	Shuttle	Station	
Visual inspection	✓		✓	Preliminary rehearsal & maintenance concept proofing
Fault detection	✓	✓		
Fault isolation	✓			
Remove & replace	✓	✓	✓	Verify EVA accessibility & replacement concept — verify sample procedures & timelines
Unscheduled repair	✓			
System operational verification	✓			
Servicing	✓	✓	✓	Verify & monitor performance of propellant supply system in zero-g environment
Handling	✓	✓	✓	Verify OTV handling concepts & equipment compatibility — verify mating procedures & equipment/EVA integration

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Table 5-2 OTV Maintenance Development Tests

The three maintenance tasks that require concept proofing and equipment evaluation at a Space Station are visual inspection, remove and replace, and handling techniques. The functions associated with the three TDM maintenance tasks were identified and are presented in Table 5-3, along with their test objectives and the operational requirements. These requirements were used to drive the conceptual design discussed in the next section.

Payload mating is covered in section 6.0.

5.2 MAINTENANCE TDM CONCEPTUAL DESIGN

The maintenance facility conceptual design is dependent on the docking and berthing TDM assets being in place at the time of maintenance TDM deployment. The maintenance TDM incorporates the berthing/maintenance dock structure and equipment into its facility, and performs maintenance operations on the simulated OTV. The RMS attached to the propellant TDM structure will provide the mechanism necessary for semi-automatic or robotic maintenance operations.

The fundamental maintenance facility consists of a non-pressurized mobile structure that is installed on a rail system, which is part of the maintenance dock structure. This maintenance facility configuration was selected for the maintenance TDM, based on the evaluation criteria set forth in the maintenance facility evaluation, Table 5-4. Four options were considered in this trade study; two pressurized hangar/module configurations; the non-pressurized mobile shelter; and an option without a shelter structure. The selected configuration (see Table 5.5) provides the basic needs for OTV maintenance in space and allows for evaluation of a balanced mix of both semi-automatic (or robotic) and EVA maintenance operations. It was strongly

Table 5-3 TDM Objectives & Requirements
Maintenance

Function	Objective	Requirement
1. OTV/maintenance dock handling	Verify handling operations & maintenance dock equipment compatibility Evaluate: • Structural integrity • Mobility & control • Interface integrity • Procedures & timelines	Perform all OTV/maintenance dock handling operations including: • Control equipment utilization • Rotate & lock operations • Interface engagement
2. Service enclosure operations	Demonstrate shelter effectiveness & conduct physical interference evaluation	Extend & retract shelter during OTV maintenance operations. Evaluate interference & limitations imposed by shelter
3. Payload handling & mating operations	Verify payload handling capabilities Evaluate: • Payload handling equipment • IVA capabilities • EVA handling device • EVA capabilities • Special tools • Procedures & timelines	Perform payload handling operations, which include: • Payload transfer from storage to OTV • Payload/OTV mating • EVA operations

Table 5-3 TDM Objectives & Requirements
Maintenance (continued)

Function	Objective	Requirement
4. Visual inspection of OTV components	Verify visual inspection concept & equipment compatibility. Evaluate: • Lighting placement & control • TV monitor effectiveness • EVA/handling device compatibility • EVA accessibility • Special inspection equipment • Procedures & timelines	Conduct OTV inspections involving: • IVA TV monitor activities • EVA operations
5. OTV component remove & replace operations with remote control arm	Verify adequacy of equipment & evaluate crewman/system interface	Exercise remote control arm system to remove & replace designated OTV components, which may include: • Avionics modules • ACS modules • Fuel cells
6. OTV component remove & replace operations utilizing EVA	Verify EVA remove & replace concept & equipment compatibility. Evaluate: • EVA handling device • EVA effectiveness • OTV repairability • Special tools compatibility • Procedures & timelines	Perform EVA remove & replace operations on: • Engine • Tank module

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felt that the work crew and OTV should be afforded basic environmental protection from meteoroids, debris, and radiation hazards, hence, the selection of having a shelter versus not having a shelter. The safety evaluation criteria also had a negative impact on the pressurized hangar/module options, because of the possibility of inducing a hazardous situation by placing the engine or other OTV components in a pressurized compartment and allowing residual propellants into a combustive environment. The unwarranted complexity, upkeep and cost of the pressurized configuration, along with proven EVA capabilities were also factors which led to the selection of the non-pressurized mobile shelter system as the maintenance TDM facility.

The maintenance shelter/enclosure shuttle installation configuration for transport and subsequent planned assembly at the space station is shown in Figure 5-4.

The maintenance shelter/enclosure consists of eight rigid panels equipped with accessories such as interconnecting latches, support carriages, and electrical equipment. These panels are packaged in the Shuttle cargo bay using two support yokes equipped with support latches which engage with each panel. The panels are arranged so that removal coincides with the assembly sequence. For example, the two panels equipped with support trusses are located at the top of the stack shown in view A-A because these panels are first engaged with the truss beams. The remaining six panels are equipped with quick type interconnecting mechanisms with alignment interfaces.

Table 5-4 Maintenance Facility Evaluation

Space Station Impact	IVA Full Pressurized Hangar	IVA/EVA Pressurized Module/Shelter	EVA Shelter	EVA No Shelter
Facilities	• Complex, stationary hangar • Hangar pressure system	• Partial OTV access module • Module pressure system • Simple mobile shelter	• Simple mobile shelter • No pressure system	• No shelter • No pressure system
Life support system	• Large volume system • 3-5 psi O_2 with complex airlock & replenishment	• 1/10 hangar volume • 14.7 psi O_2 with airlock & replenishment	• Extravehicular mobility unit(s)	• Extravehicular mobility unit(s)
Support equipment	• Standard handling • Standard space tools	• Special & standard handling • Special & standard space tools	• Special handling • Special tools	• Complex handling • Special tools
OTV Maintenance	• Shirtsleeve repair • Propellant servicing outside hangar	• Shirtsleeve & EVA repair • Propellant servicing in place	• Robotic & EVA repair • Propellant servicing in place	• Robotic & EVA repair • Propellant servicing in place
Facilities Maintenance	• EVA repair • O_2 pump & supply system • Temperature regulation system • Airlock seals & vents	• O_2 pump & supply system • Temperature regulator system • Shelter mobility system	• Shelter mobility system	• No maintenance
Spares Storage	• Spares storage space available	• Spares storage space available	• Spares storage space available on inner walls	• Requires spares storage structure
Safety	• Residual propellant hazard • Meteorite & radiation protection	• Residual propellant hazard • Meteorite & radiation protection	• Residual propellant safe • Meteorite & radiation protection	• Residual preopllant safe • No environment protection
Growth potential	• Difficult add-on	• Simple add-on	• Simple add-on	• Easy add-on
Cost	• High cost	• Medium cost	• Lower cost	• Lower cost

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Table 5-5 Shelter Selection Rationale

The selected nonpressurized mobile shelter configuration provides the basic needs for OTV maintenance in space

Shelter attributes

- Provides protection against meteoroids, debris & radiation
- Configuration is residual propellant safe
- Reduced complexity minimizes facility maintenance
- Provides for balanced mix of semiautomatic (or robotic) & EVA OTV maintenance operations
- Provides for spare parts & equipment storage on inner walls
- Configuration has growth potential
- Feasible to transport on Shuttle & assemble at space station
- No apparent showstoppers

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Equipment	Wt (lb)
Support cradle (stays with Shuttle)	950
Two side panels with support trusses & drive carriages	1,165
Two top & bottom panels	510
Four filler panels	720
Electrical & instrumentation	400
Total	3,745

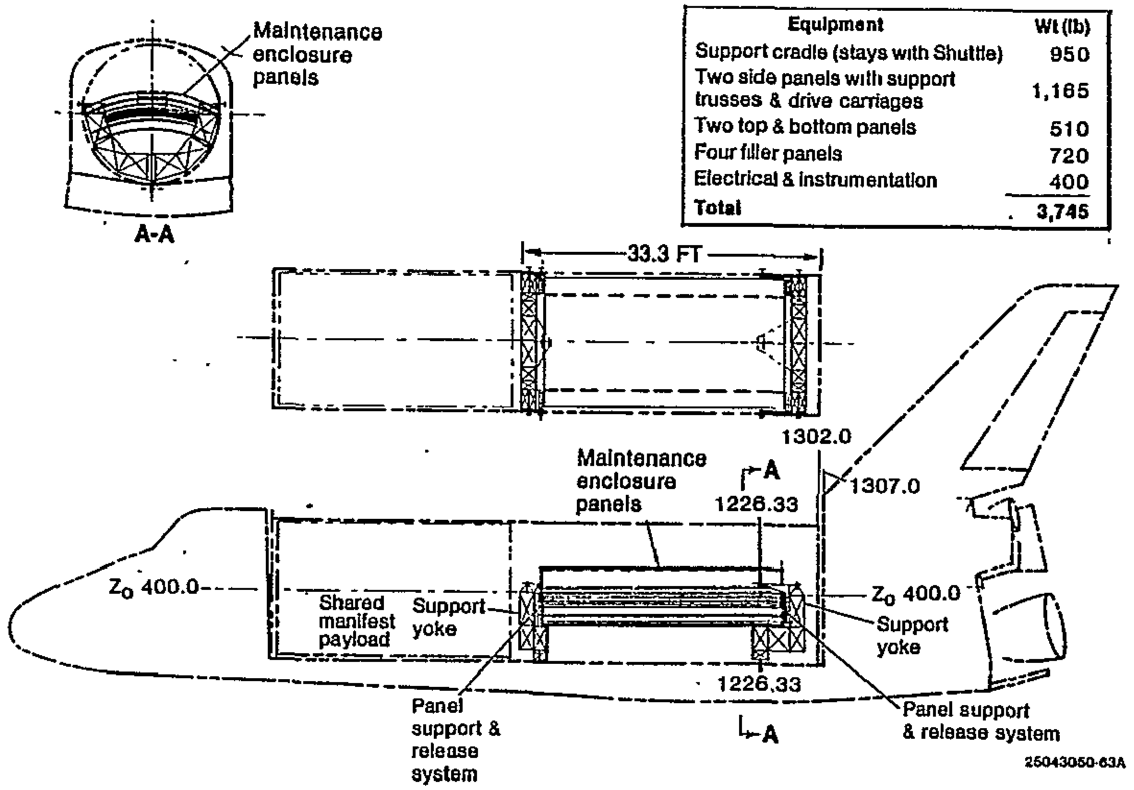

Figure 5-4 Maintenance Enclosure Launch Configuration

The maintenance shelter is assembled at the space station as depicted in Figure 5.5 and as described below.

With the Shuttle docked remotely from the TDMs, a Space Station RMS (mounted on a carriage) is used to extract the maintenance panels from the Shuttle payload bay and transport these panels to the TDMs. The panels are taken from the Space Station RMS and placed on the maintenance dock structure. The crewmen, who assemble the panels, are attached to the TDM structure with traveling cherry picker type restraints.

The maintenance enclosure panels are packaged in the Shuttle such that the two top key panels (equipped with carriages) can be extracted first and connected to the TDM structure. The next four panels are connected to the key panels with quick type latches that have self aligning features. The enclosure is then completed by attaching the last two panels to the assembled structure completing the cylinder.

The support equipment that are incorporated into the maintenance shelter facility are now described within the context of typical maintenance operations. The engine, tank module and aerobrake handling equipment are presented in Figure 5-6. The maintenance enclosure has a scissor type crane mounted on an extendable boom equipped with rails for manipulating large OTV components, such as engines and propellant tank modules, during remove and replace operations. The Space Station is also equipped with a holding fixture for storing these items during maintenance operations.

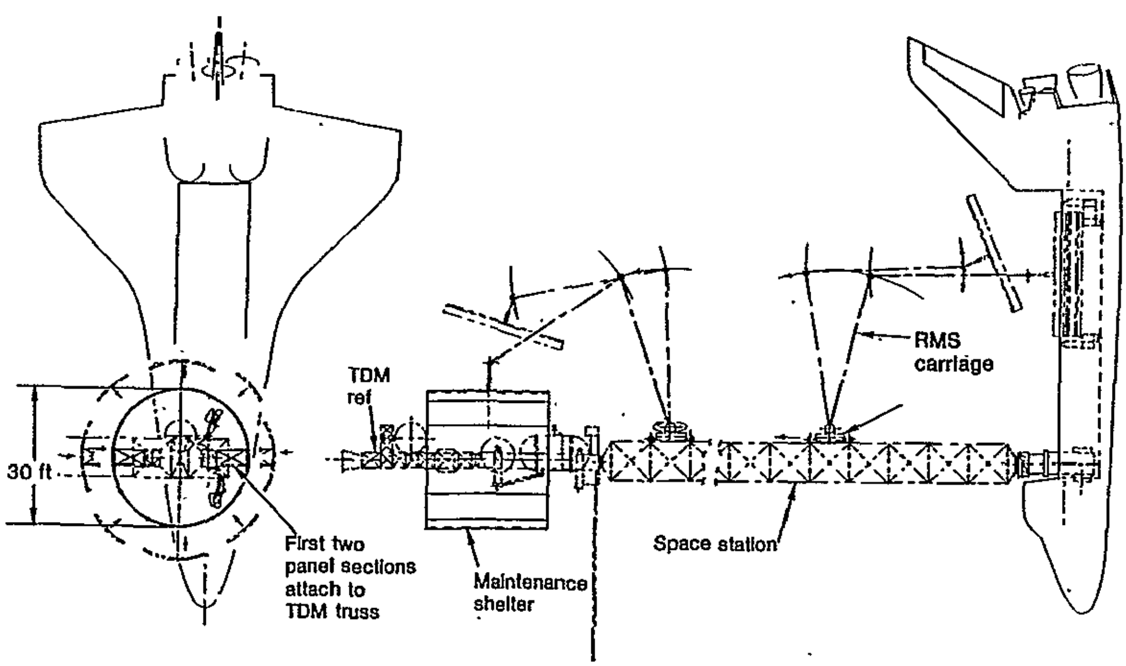

Figure 5-5 Maintenance Shelter Assembly

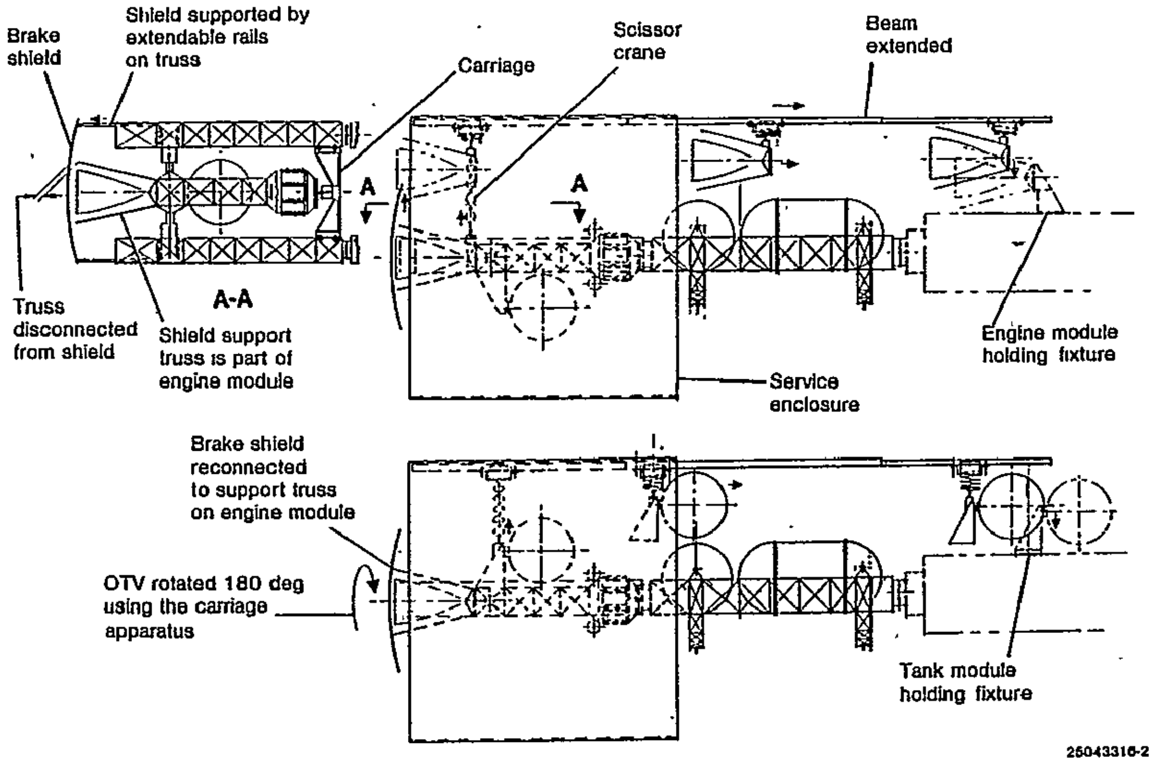

Figure 5-6 Maintenance TDM - Engine & Tank Changeout

Two OTV module remove and replace examples are shown with an aerobrake attached to the simulated OTV. The first example is an engine module changeout. The engine module is equipped with an open truss cage which attaches to the aerobrake through a series of structural disconnects. The changeout starts by latching the aerobrake to the truss beams (View A-A), attaching the service enclosure scissor crane to the engine module, and disconnecting the engine module from the main OTV body structure. The changeout then proceeds by actuating the scissor crane which transports the engine module to a holding fixture on the Space Station. The changeout simulation is completed by reattaching the scissor crane to the engine module on the Space Station holding fixture and performing the procedure in reverse.

The second example shows a propellant tank module changeout. This requires rotating the OTV 180° about its longitudinal axis so that the tank module is within reach of the scissor crane. This 180° rotation is accomplished by detaching the OTV from the berthing system, translating the OTV to the end of the TDM structure using the carriage, rotating the OTV with the carriage system and pulling the OTV back to the service position with the carriage. The tank changeout translation procedures to the station and back are the same as that described for the engine. The OTV must be translated to the end of the structure so the tank will clear the structure during rotation.

Smaller equipment items such as avionics packages and ACS modules can be replaced automatically using the RMS located on the propellant transfer module as shown in Figure 5-7. A typical changeout is shown for an ACS module. The changeout starts by attaching the RMS to a fitting on the ACS module and the module is then disconnected from the OTV. The ACS module is next transported by the RMS to a holding fixture located on the propellant transfer module and attached to the fixture. The changeout is completed by reattaching the RMS to the ACS module and reversing the procedures. The same procedures apply to avionics equipment changeouts.

In order to reach all equipment items with the RMS, it may be necessary to rotate the OTV about its own axis, about the service carriage axis or about the berthing system axis. All three modes of rotation can be accomplished by the carriage and berthing systems as shown on the docking and berthing operations charts. For some modes, the maintenance enclosure is positioned over the propellant transfer module to allow clearance.

Figure 5-7 also shows the cherry picker equipment necessary for EVA crew member translation to and from the work site. The cherry picker has personnel restraints and is mounted on a rail carriage system that allows the required mobility and OTV access for maintenance EVA operations.

The equipment identified for support of the maintenance TDM are included in the maintenance TDM support equipment summary Table 5-6. All equipment is launched on the TDM except where equipment is already available on the station.

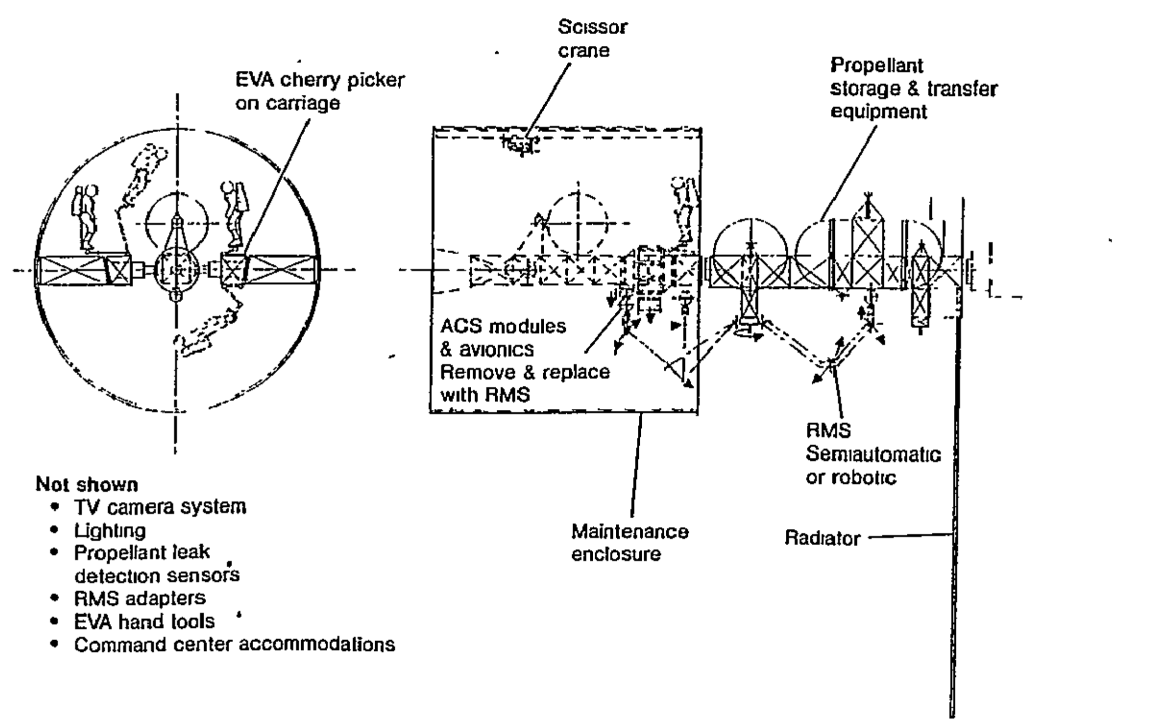

Figure 5-7 Basic Maintenance Facility & Support Equipment

Table 5-6 Maintenance TDM Support Equipment Summary

Equipment	Location: TDM	Location: Space Station	Comments
Crane & extender beam	Installed on shelter	Command center control interface	Part of shelter assembly — capable of handling engine & tank module
TV camera system	Cameras	Command center monitor interface & control	Part of truss structure & shelter assembly
Lighting system	Lights installation	Command center control interface	Part of shelter assembly & structure
Engine & tank module holding fixture		Module storage on station	Located on station — fixture compatible with engine & tank module
Leak detector system	Sensors in shelter area, cherry picker, RMS	Command center monitor interface	Distributed system — EVA also equipped with unit
Engine borescope		Stored on station	Compatible with RMS & EVA hand carry
EVA hand tools • Connectors & plumbing • Aerobrake strut tool	Stored on TDM structure		
RMS & robotic arm adapters • Avionic modules • Fuel cell • Battery • ACS modules	Stored on TDM structure		Possibly only one adapter required, with proper attention to standardization

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5.3 MAINTENANCE TDM OPERATIONS

The actual maintenance TDM involves Level I maintenance activities. It was not under the scope of this contract to look at Level II.

The simulated OTV components that were identified for maintenance concept proofing at the space station are listed in Table 5-7. The avionic modules will be removed and replaced by both EVA and IVA operations and the ACS modules are replaced via IVA/RMS. All other OTV maintenance activities will involve EVA operations. One damage repair operation to be accomplished on the aerobrake while on the vehicle, has been injected into the maintenance scenario, but the other maintenance activities all involve remove and replace action. The IVA remove and replace operations will be accomplished with crew control of an RMS or the RMS may be programmed to do the task entirely under computer control. Visual inspection techniques will be performed and evaluated in conjunction with the other individual maintenance operations.

The overall sequence of maintenance TDM operations is shown in Figure 5-8. The operational scenario addresses the initial maintenance TDM facility and equipment delivery, installation and checkout sequence, along with each maintenance task to be performed at the space station. Each maintenance task will be performed six times with varying conditions to verify the adequacy of equipment, and to validate and calibrate the procedures and timelines. More detailed information on the maintenance tasks in the form of functional flow diagrams, equivalent ground and TDM tasks, and timelines can be found in the appendices. Some samples of the timelines and tasks are presented here in the text. The sequence of maintenance tasks was selected in an arbitrary manner and can be changed to accommodate particular needs.

Table 5-7 Subsystems Selected for Maintenance Tests

• Avionic modules	— Several representative RF & computer modules for EVA remove & replace & IVA/RMS remove & replace
• Core section	— Fuel cell & battery EVA remove & replace — ACS IVA/RMS remove & replace
• Engine module	— EVA remove & replace
• Tank module	— EVA remove & replace
• Aerobrake	— EVA repair

Note: Visual inspection to be a distributed function on all tasks

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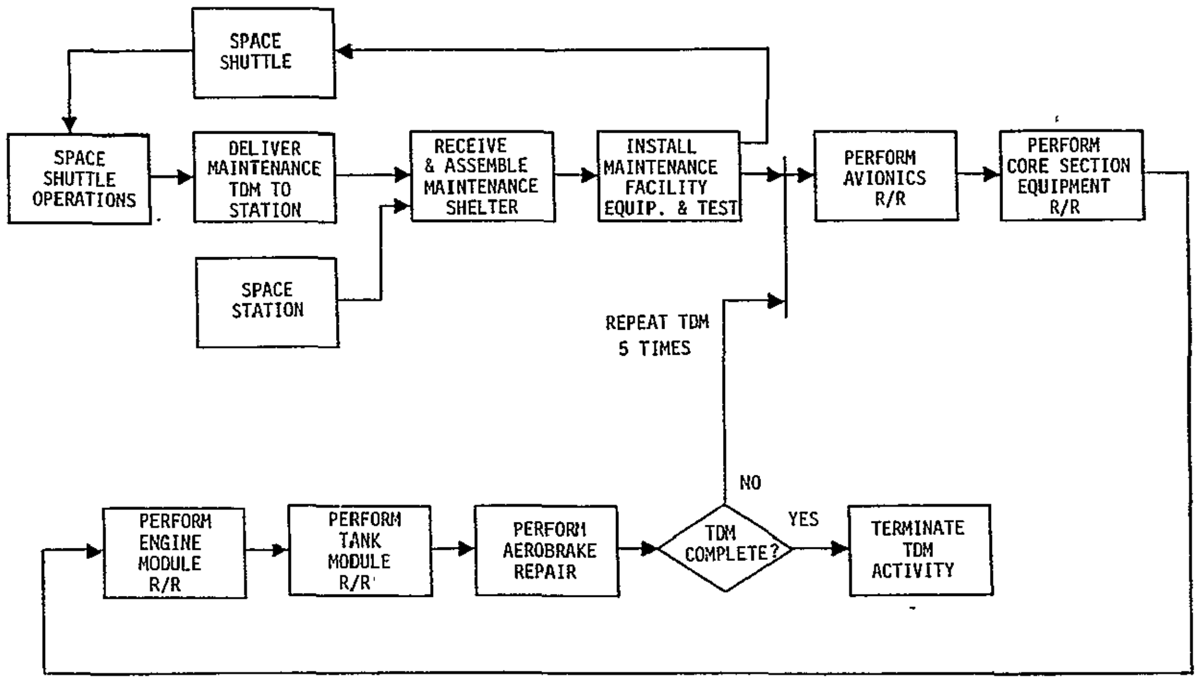

Figure 5-8 Maintenance TDM Operations

The assembly and installation of the maintenance enclosure and equipment were pictorially presented and described in Paragraph 5.2. The timelines for those maintenance enclosure activities are shown here in Table 5-8. The assembly and checkout of the maintenance enclosure at the space station was determined to be a two day operation. The enclosure panels are assembled on the first day and the equipment installation and checkout occur on the second day. The off-loading operation requires two Shuttle crew members on the Shuttle to perform the TDM equipment off-loading tasks. Two maintenance TDM EVA personnel will assemble the enclosure, install the equipment and test the system on the station maintenance dock, while a third TDM crewmember will perform the command and monitor functions inside the station.

The generic maintenance tasks that were identified for inclusion in the maintenance TDM were listed in Section 5.1 along with the functional requirements. A sample of this listing, which addresses engine remove and replace activities, is presented in Table 5-9. General Dynamics Convair Atlas and Centaur procedures, along with turn around operations analysis for a Space Tug, were scrutinized for equivalent groud operational tasks that would satisfy the specific functional requirements. The applicable procedure numbers were annotated at the top of each ground task column and the actual task descriptions were entered within that column.

Table 5-8 Maintenance Enclosure Operations

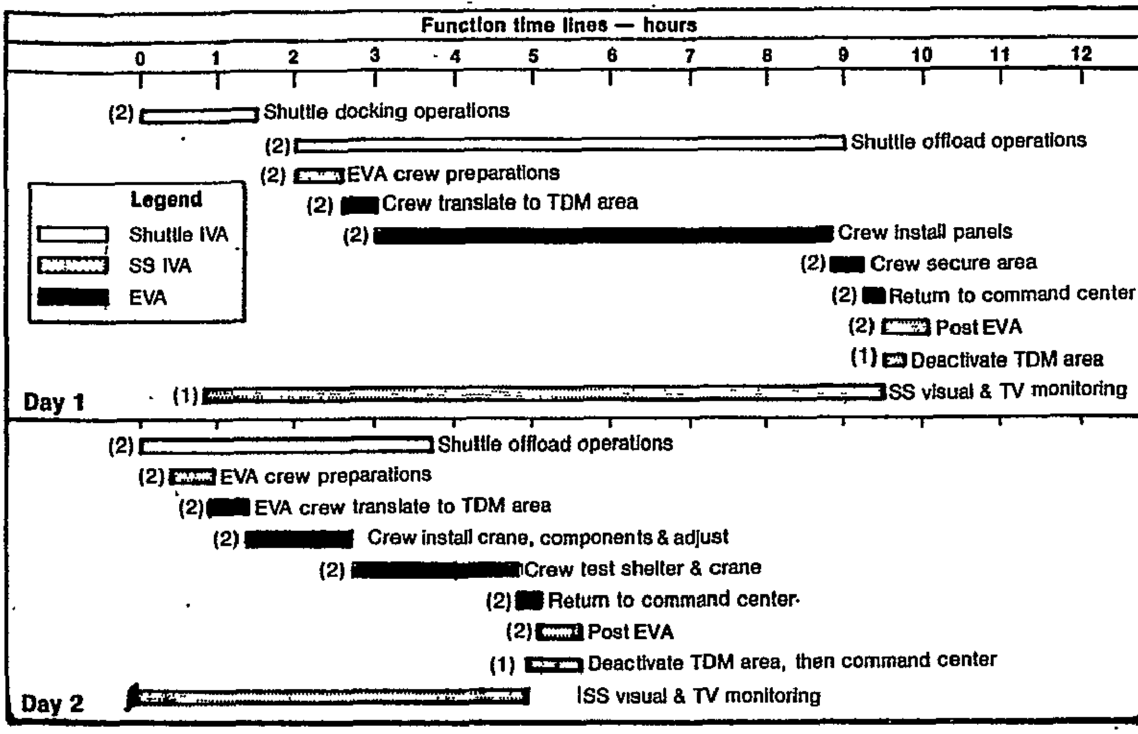

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Table 5-9 TDM Maintenance Summary - Propulsion

Functional Requirements	Equivalent Ground Task	TDM Task	IVA	EVA	Support Equipment Requirements
Maintenance Main Engine	Procedure: HPS 1-00347				
*Remove & replace preparations					
• Crew orientation	• Review procedures	• Review maintenance plan	✓		• Computer system
• EVA crew	• Obtain planning paper	• Don EVA gear	✓		• EVA gear & tools
	• Record removal procedure on check sheets	• Perform EVA airlock transition	✓	✓	
		• Monitor EVA progress (command center)	✓		• TV system & comm link
• Maintenance facilities	• Pick up handling tool with overhead crane	• Activate TDM maintenance facility	✓		
		— Shelter lighting			• Shelter lighting installation
		— TV system			• CCTV system
		— Crane control			• Scissor crane & extender beam
		— Cherry picker control			• Cherry picker on carriage
	• Position crane over engine	• Position crane over engine	✓		

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Table 5-9 TDM Maintenance Summary - Propulsion (continued)

Functional Requirements	Equivalent Ground Task	TDM Task	IVA	EVA	Support Equipment Requirements
*Remove engine	• Remove plumbing & electrical wiring	• Transfer EVA crew to cherry picker		✓	
	• Drain lines & reduce pressure to zero	• Check local cherry picker controls & communication		✓	
	• Disconnect 12 plugs & tie back	• Translate crew to engine work area		✓	
• Detach aerobrake & stow		• Attach aerobrake to rail truss		✓	• Truss extender on truss structure
		• Detach aerobrake from OTV shield support truss		✓	
		• Extend aerobrake away from engine	✓		
• Attach crane to engine	• Install handling tool on engine • Support engine weight with crane	• Attach crane to engine		✓	
• Remove engine	• Remove 2 actuators • Remove 4 engine mounting bolts • Verify engine free for hoisting	• Loosen engine mounting hardware		✓	• EVA tools or latches on OTV
		• Detach engine from OTV		✓	• Special tool or OTV mechanical provisions
• Translate crew to safe area		• Translate EVA crew to safe area		✓	• Cherry picker
• Separate engine from OTV	• Raise engine & place on trailer • Secure engine to trailer	• Withdraw engine with crane	✓		• Scissor crane
• Translate engine & mount to holding fixture	• Install support to LO_2 & fuel lines • Cover gimbal block & tie	• Translate engine to holding fixture			• Engine holding fixture

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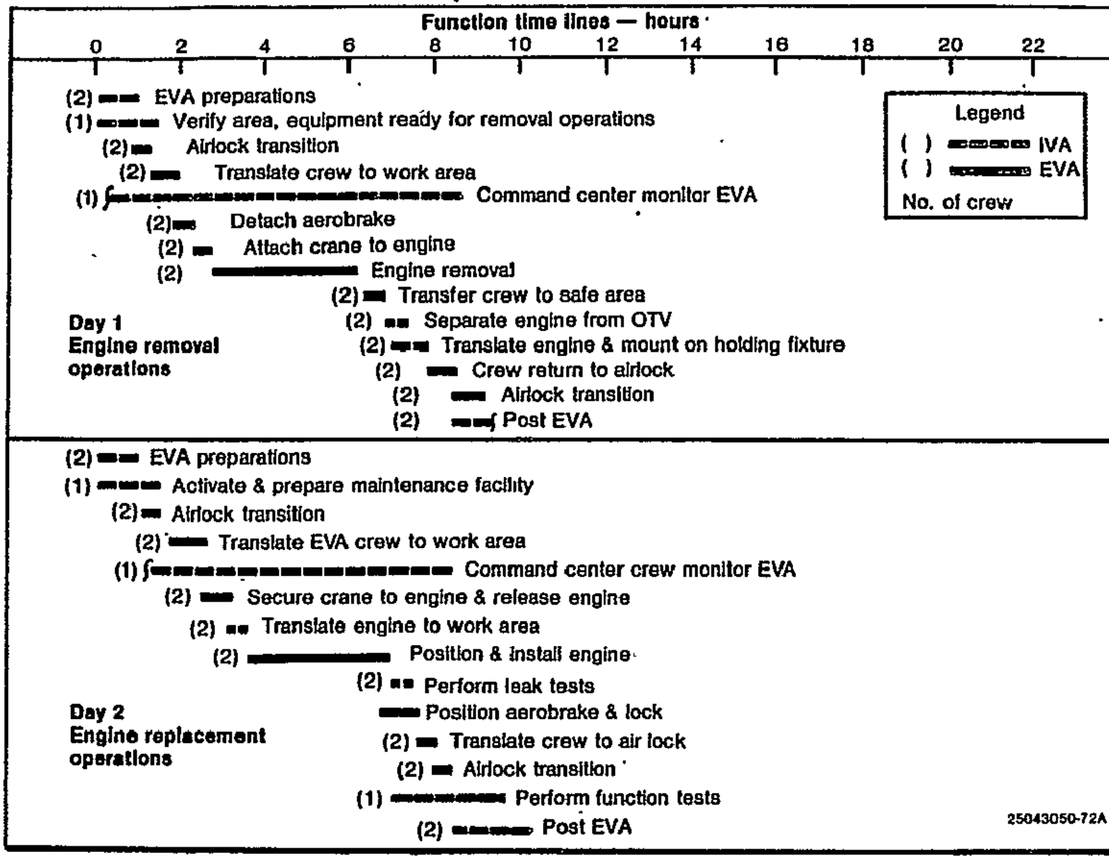
The TDM tasks were then developed using the ground tasks as a reference checklist to assure that all applicable procedures were adequately presented. Of course, the TDM tasks assume their own operational characteristics, because of the differences in design concepts and consideration for the working environment, but it is important to note that the ground tasks formed the foundation for the formulation of these OTV maintenance procedures. The table also reveals the support equipment that are required to accomplish the tasks and whether or not the activity requires IVA or EVA involvement. The procedure referenced in the table is a ground operations procedure for the Centaur. Additional maintenance tasks data can be found in Appendix B.

The engine remove and replace timeline is presented in Table 5-10.

The timeline reveals the selected engine module remove and replace activities as being a two day operation. The engine module will be removed on the first day and placed on the engine holding fixture. The process will be reversed on the second day, by removing the engine module from the holding fixture and installing it on the OTV core section interface. The engine replacement time of 9½ hours is the longest operations time identified in the maintenance TDM and the EVA portion of replacement time is 7-3/4 hours, which is also the longest EVA time identified.

Table 5-10 Main Engine - Removal & Replacement



The overall maintenance TDM timeline is shown in Table 5-11.

The overall timelines for the TDM maintenance operations initially encompass an eight day working period. The timelines include two days for maintenance shelter assembly on station. The TDM maintenance activities, when performed sequentially, can be accomplished within a six day working period with a day in between each activity for documentation. The maintenance TDM will be executed on an average fifteen day cycle, conducted six times, during the mission in the same sequence. The fifteen day cycle provides for one day of rest between each EVA operation and three days of rest at the completion of a cycle. The repitition of the TDM allows for variation of conditions and learning curve transition. The total orbital time span for this TDM is approximately three months. (See Section 7.0).

The longest time of operation is 9½ hours, for engine replacement as previously stated and the shortest operating day is 6½ hours for avionics remove and replace. Avionics remove and replace activities will require 4½ hours for EVA operations and 1½ hours for IVA remove and replace actions, using an RMS, on essentially the same task. Both EVA and IVA avionics remove and replace tasks will be accomplished the same day.

Table 5-11 Overall Maintenance Time Line

Day	Task	Time — Hours (0 1 2 3 4 5 6 7 8 9 10)	Man-hours
1	Offload & install shelter structure	(4)	32
2	Final shelter installation & verification	(4)	24
3	Avionics EVA remove & replace — RMS remove & replace	(3) (1)	17
4	Fuel cell & battery EVA remove & replace — ACS RMS remove & replace	(3) (1)	17
5	Remove engine	(3)	26
6	Replace engine	(3)	28
7	Tank module remove & replace	(3)	21
8	Aerobrake repair	(3)	23
		Total man-hours	188

IVA EVA

Note: These maintenance activities should be repeated ≈5 times under varying conditions & parameters to establish the desired data base.

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The engine module remove and replace task is a two day operation, because we have established that this unit should have a high fidelity interface. The tank module remove and replace task only requires one day for change-out activities, because we envision the interface here to be of lower fidelity than the engine module for this TDM.

5.4 SPACE STATION SUPPORT FOR THE MAINTENANCE TDM

Figure 5-9 identifies the total space station support for this TDM. The space station interfaces and some of the equipment have been identified in previous figures. The expected power required is shown with a requirement of approximately 600 watts during the performance of the maintenance tasks. About 40 ft^3 of volume will be required for the controls and displays for the Space Station RMS and the TDM RMS, crane, and the tests. Two EVA suits and EMUs will be required. Ground communications will be required for any additional consultation during the tests. The skills and levels for the three crewmen are indicated. These designations are from the instructions generated by NASA for the TDM forms and used in the space station payload data sheets.

- Translating RMS & control station
- Power, controls, data, communications & TV interfaces
- Power — 600W during maintenance experiment
- Data acquisition & processing, remote TV & caution & warning systems
- Communications — ground & TDM (radio frequency & hard line)
- Volume $\approx$40 ft^3 for controls & displays plus cooling system
- 2 EVA suits, helmet heads-up displays & EMUs plus storage & cleaning facilities
- Astronaut egress, ingress & translation system to TDM
- Crew: One spacecraft systems professional (skill 7, level 3*)
  Two engineering technicians (skill 5, level 2)

* One additional crewman like this while Shuttle docked to space station to assemble enclosure

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Figure 5-9 Maintenance TDM Space Station Support

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6.0 OTV/PAYLOAD INTEGRATION TDM

OTV payloads assume a wide variety of configurations and perform many different missions as shown in Table 6-1. This led us to establish some generalizations and assumptions regarding a probable payload for use on a TDM. The payloads we considered were the payloads that consist of satellites or other spacecraft which are delivered to the Space Station for assembly or maintenance, and where they receive checkout and integration with a carrier vehicle for subsequent transport to their designated orbit or trajectory. We further derived assumptions about this payload for our specific use as described below:

a. A representative payload will be available for use at the Space Station to coincide with the payload integration TDM. We envision it to be an engineering prototype used for satellite servicing TDMs.

b. The payload will be a single payload or payload pallet consisting of several payloads already installed and ready.

c. The payload or pallet will have a standardized interface for mating with the OTV.

d. The payload will have representative replacement units for payload maintenance demonstrations.

e. The payload would be located within RMS reach of the OTV maintenance dock.

Payload type	Weight	Launch dates	OTV operations
Small communication satellites	< 2,000 lb	1994-2000 & on	Assemble & checkout up to 4 payloads per OTV flight. Deploy at GEO
Medium communication satellites	<4,000 lb	1994-2000 & on	Assemble & checkout up to 3 payloads per OTV flight. Deploy at GEO
Large communication satellites	<12,000 lb	1994-2000 & on	Carry 1 or 2 payloads per OTV flight. Some checkout & servicing at LEO later satellites
Operational GEO platform	≈14,000 lb	1994-2000	Transfer platforms to OTV. Check out & transfer to GEO
Very large platform	TBD multiple OTV deliveries	1998	Remove components from shuttle Mate & construct subassemblies (probably asymmetric) for OTV transfer to GEO. Assemble very large platform in GEO
Unmanned servicing at GEO	6,000 lb up 2,000 lb down	1995-2000 & on	Maintain, replenish, update & augment satellites in GEO via OTV servicing flight. Return servicer to S/S
Manned sortie to GEO	13,000 lb round trip	1995-2000 & on	Provide emergency servicing, assist in GEO assembly of space structures via manned OTV. Return manned module to space station.
Planetary missions	1,000 to 6,000 lb	1994-2000 & on	May require specific P/L orientation before launch. Use OTV to provide boost to escape velocity for planetary payloads.

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Table 6-1 Characteristics of OTV Payloads

These assumptions allowed the development of operational scenarios that were necessary in defining and establishing requirements for the TDM.

6.1 MISSION REQUIREMENTS

The initial requirement for payload integration proofing at the Space Station was established in Section 5. These requirements were identified as handling operational requirements in Table 5.1-1 and further outlined in Table 5.1-2, Item 3, as to objectives and operational requirements for the TDM. Refinements to the requirements for the OTV/payload integration operations are presented in Table 6-2. The operations of handling, mating and demating, and remove and replace activities comprise the payload TDM. It is felt that checkout of the payload would be a unique function for most payloads and would be accomplished by an earth station with appropriate capabilities. These checkout capabilities would best be developed in the ground development segment.

More definition of the operational requirements are identified in Figure 6-1 and additional detail is provided in the appendices.

6.2 CONCEPTUAL DESIGN

The payload integration design concept for implementation of the TDM is presented in Figure 6-2. For this TDM it is assumed that a simulated payload would be available at the Space Station and that no additional equipment is needed to be launched.

Table 6-2 OTV Payload Integration Operations Development Test Matrix

OTV Payload Operations	Development Tests		Objective of the Test Program	Rationale for Test Location
	Ground	Space Station		
Handling	X	X	Test the concepts of payload transfer from space station berthing to OTV interface	Ground tests to establish procedures. Space station tests required to confirm procedures in actual working environment
Mating	X	X	Develop the procedures required for mating payloads on an OTV for attachment ease & interface verification	Ground tests to establish procedure & interface design. Space station tests required to verify attachment interface
Checkout	X		Validate the methods of payload checkout after mating & before launch of OTV	Space station tests not required. Checkout from space station is the same as on ground simulator
R&R payload components	X	X	Test concepts of servicing payloads attached to an OTV when berthed at space station	Ground tests to establish RU replacement methods. Space station test required to confirm operations
Demating	X	X	Test the concept of payload removal from OTV due to failure detection	Ground tests to establish procedures. Space station tests required to confirm procedures in actual working environment

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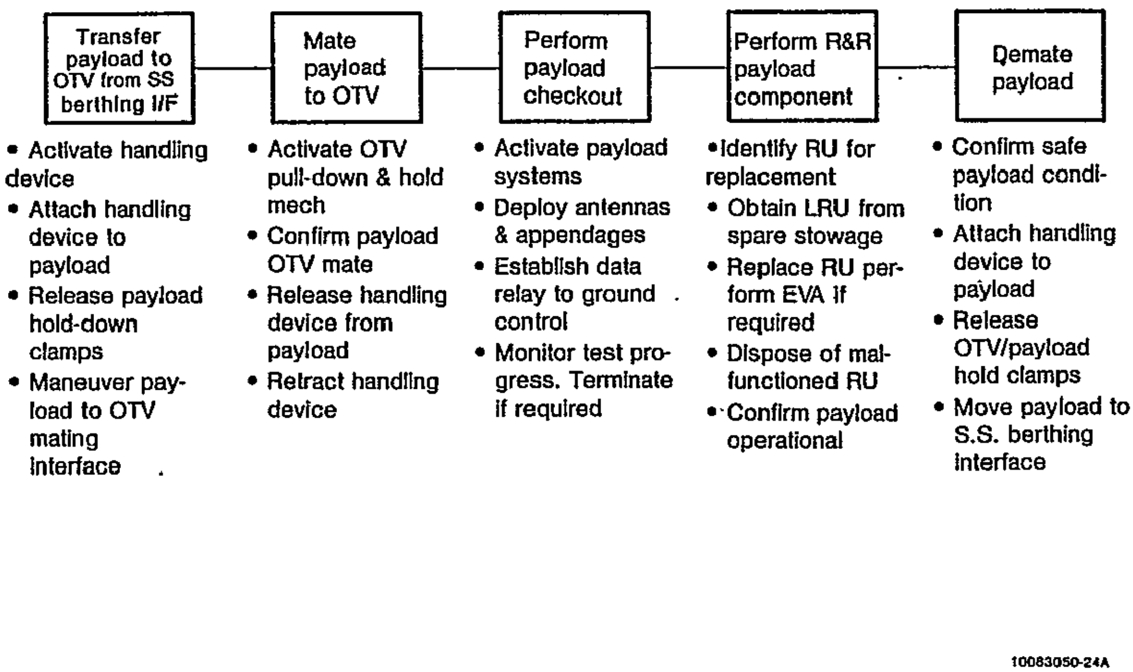

Figure 6-1 OTV/Payload Integration Functions

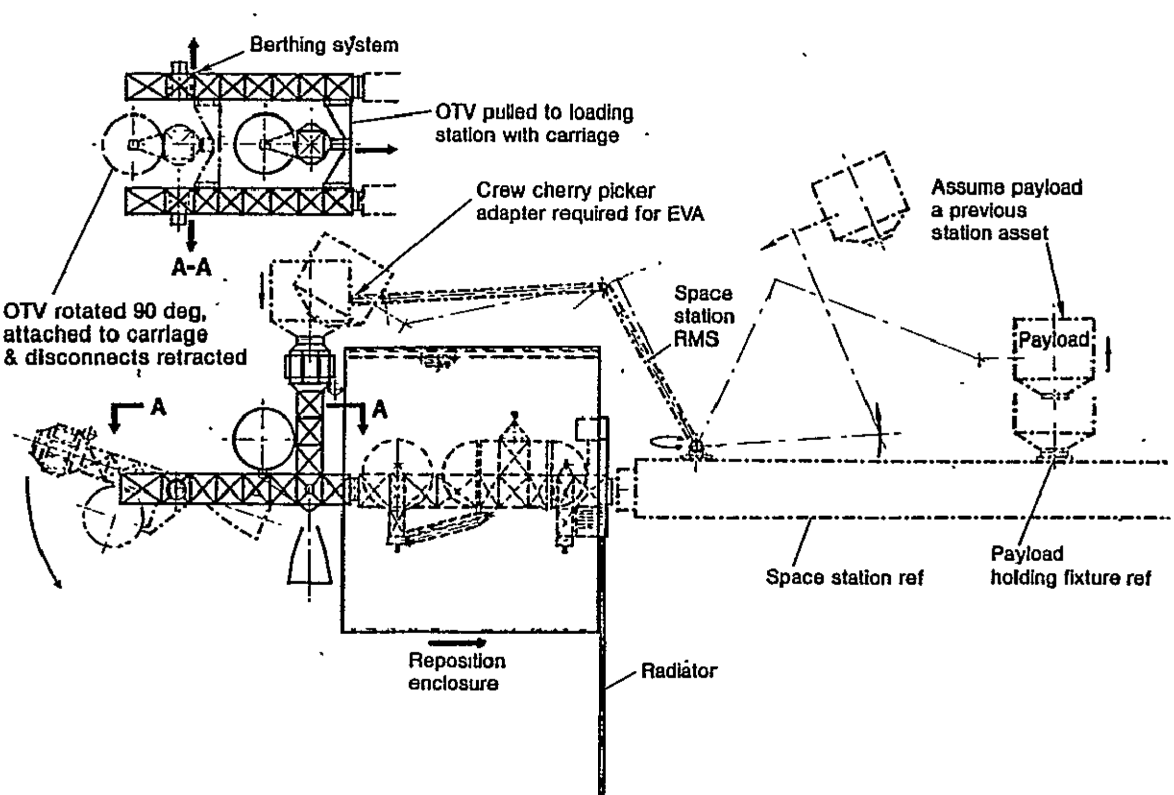

Figure 6-2 OTV/Payload Integration Operations TDM

The Space Station is equipped with an RMS for transporting equipment from the storage area to the OTV. Prior to attaching a simulated payload, the maintenance enclosure is moved over the propellant transfer module to allow clearance for the OTV. The OTV is next rotated about the berthing system axis, engaged with the carriage and pulled by the carriage (see A-A) to a position close to the maintenance enclosure. The simulated payload is then transported from a fixture on the Space Station to the OTV using the Space Station RMS, mated to the OTV and check out of the integration is performed.

The RMS is detached from the payload and returned to the station where a manned cherry picker device is attached to it. Two crewmen are then carried to the payload and perform a simulated remove and replace operation. After the EVA operation on the payload, the crewmen are returned to the Space Station. Then the payload is demated from the OTV and returned to the support fixture on the station.

6.3 PAYLOAD INTEGRATION TDM END-TO-END OPERATIONS

The OTV/Payload integration operations TDM timeline is presented in Table 6-3.

This timeline depicts the essential OTV/payload integration activities from the initiation of the TDM to facility shutdown. The TDM is a one day, 8½ hour operation. The scenario calls for approximately 2½ hours of EVA maintenance activities on the payload, with the payload mated to the OTV. The TDM will be conducted six times under varying conditions to establish the required data base.

Table 6-3 OTV/Payload Integration Operations TDM

Task	Time (hours) 0 1 2 3 4 5 6 7 8 9 10	Man-~hours
Activate facility & rotate OTV	(1)	1
Mate payload to OTV	(1)	1.5
Pre-EVA operations	(2)	2.0
Translate crew to payload	(2) EVA (1) IVA	1.5
Perform EVA remove & replace task	(2) EVA (1) IVA	7.5
Translate crew to command center	(2) EVA (1) IVA	1.5
Post-EVA operations	(2)	2.0
Demate payload from OTV	(1)	1.0
Mate payload to holding fixture	(1)	0.5
Rotate OTV & deactivate facility	(1)	1.0
	Total man-hours	19.5

Legend: IVA, EVA

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6.4 SPACE STATION SUPPORT FOR THE PAYLOAD INTEGRATION TDM

The requirements listed in Figure 6-3 identify the total Space Station support for this TDM. This requirement stands alone and is not additive to the other preceding TDM requirements. Except for the simulated payload (which is expected to be on the station from another TDM), payload holding fixture, and RMS cherry picker adapter, the requirements have all been covered by the previous TDMs. The Space Station interfaces and some of the equipment have been identified in previous charts. The expected power required is shown with a requirement of approximately 400 watts during the running of the test. About 40 ft^3 of volume will be required for the controls and displays for the Space Station RMS and the tests. Two EVA suits and EMUs will be required. Ground communications will be required for any additional consultation during the tests. The skills and levels for the three crewmen are indicated. These designations are from the instructions generated by NASA for the TDM forms and used in the Space Station payload data sheets.

- Simulated payload with compatible interfaces & representative replaceable units
- Payload holding fixture
- Space station RMS & associated controls
- RMS cherry picker adapter & adapter holding fixture
- Elecrical power — 400W
- Control computer system, data processing, TV system interfaces & displays
- Communications — ground & TDM (radio frequency & hard line)
- Volume requirements $\approx$40 ft^3 for equipment plus cooling system
- 2 EVA suits, including helmets with heads-up displays plus cleaning & storage facilities
- Airlock to provide egress & regress capability & a translation system for access to TDM
- Crew skills: One spacecraft systems professional (skill 7, level 3)
  Two engineering technicians, (skill 5, level 2)

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Figure 6-3 Payload Integration Operations TDM Space Station Support

7.0 SUMMARY SPACE STATION ACCOMMODATIONS

For each of the TDMs, the operational timelines were presented and the Space Station support equipment identified. This section summarizes all the operational activities and the required space station support.

Figure 7-1 reveals all of the planned OTV related TDM activities to be performed on the Space Station and the time allotted for the performance of each of the identified TDMs. The TDM performance time allocations are based on a 90 day Shuttle revisit schedule. The specific mission timelines reflect the proposed recycling scheme for the experiments and operations, along with the recommended break points.

Figure 7-2 identifies the total Space Station support requirements for the OTV related TDMs. These requirements are a summation of all the other preceding TDM requirements. The space station interfaces and all of the equipment have been identified in previous sections. The expected power required is shown with a requirement of approximately 600 watts plus 500 watts during the running of the propellant test. About 60 ft^3 of volume will be required for the controls and displays for the Space Station RMS and the tests. Four EVA suits and EMUs are recommended; two for use and two for backup or alternate use. Ground communications will be required for any additional consultation during the tests. The skills and levels for the three crewmen are indicated.

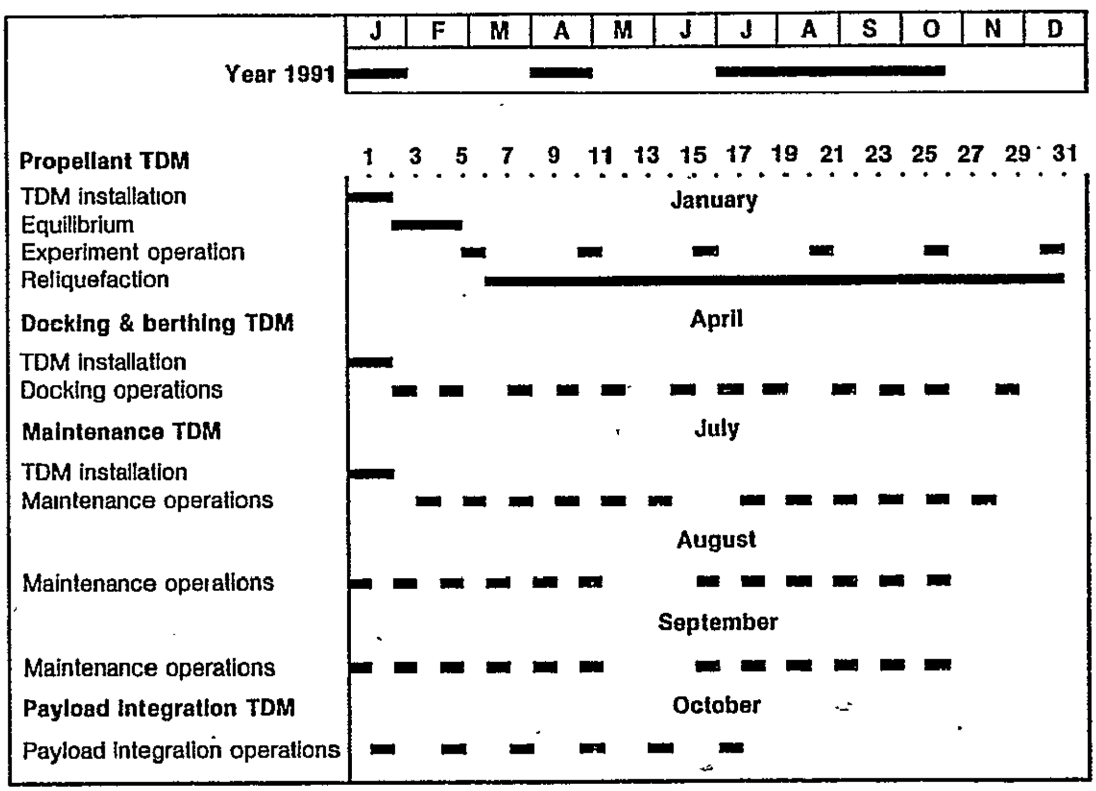

Figure 7-1 Summary of TDM Activities

- Translating RMS & associated controls
  - RMS cherry picker adapter & adapter holding fixture
- TDM to station interfaces
  - Mechanical attachments
  - Electrical interfaces (power, controls, data, communications & TV)
- Electrical power
  - 600W maximum continuous +500W during reliquefaction
- Data acquisition & processing system, remote TV & caution/warning system
- Communication system
  - Ground & TDM (radio frequency & hard line)
- Volume requirements ≈ 60 ft^3 for equipment plus cooling system
- TMS with control station & storage provisions
- Simulated payload with compatible interfaces & representative replaceable units & a payload holding fixture
- (4) EVA suits with EMUs, including helmets with heads-up displays plus cleaning & storage facilities
- Airlock for EVA egress & regress & translation system for EVA crew access to TDM
- Crew Skills:
  - One spacecraft systems professional (skill 7, level 3)
  - Two engineering technicians (skill 5, level 2)

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Figure 7-2 Summary Space Station Requirements to Support the OTV TDMs

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8.0 COMBINED TDMs CONCEPTUAL DESIGN

The arrangement in Figure 8-1 shows all TDMs packaged for a single dedicated flight. This dedicated flight contains all the equipment previously shown for the multiple flights except for the receiver tank. The receiver tank in this case is the tank module on the simulated OTV.

The maintenance enclosure in this case consists of four rigid panels interconnected by four inflatable double wall sections. The simulated OTV, the maintenance enclosure, the storage tank and the propellant conservation module are mounted on a single truss structure which interfaces with the Shuttle support fittings. The aft end of the support structure is equipped with berthing systems for attaching to the Space Station. The support structure also contains transfer lines, Shuttle interface plumbing and electronics equipment.

Figure 8-2 shows the combined TDM docked to the Space Station with the maintenance enclosure expanded to full position. The simulated OTV is supported between the truss beams on motorized carriages which move the OTV to the docking, berthing, payload mating and propellant transfer positions. Propellant is transferred from supply tank to the tank on the simulated OTV.

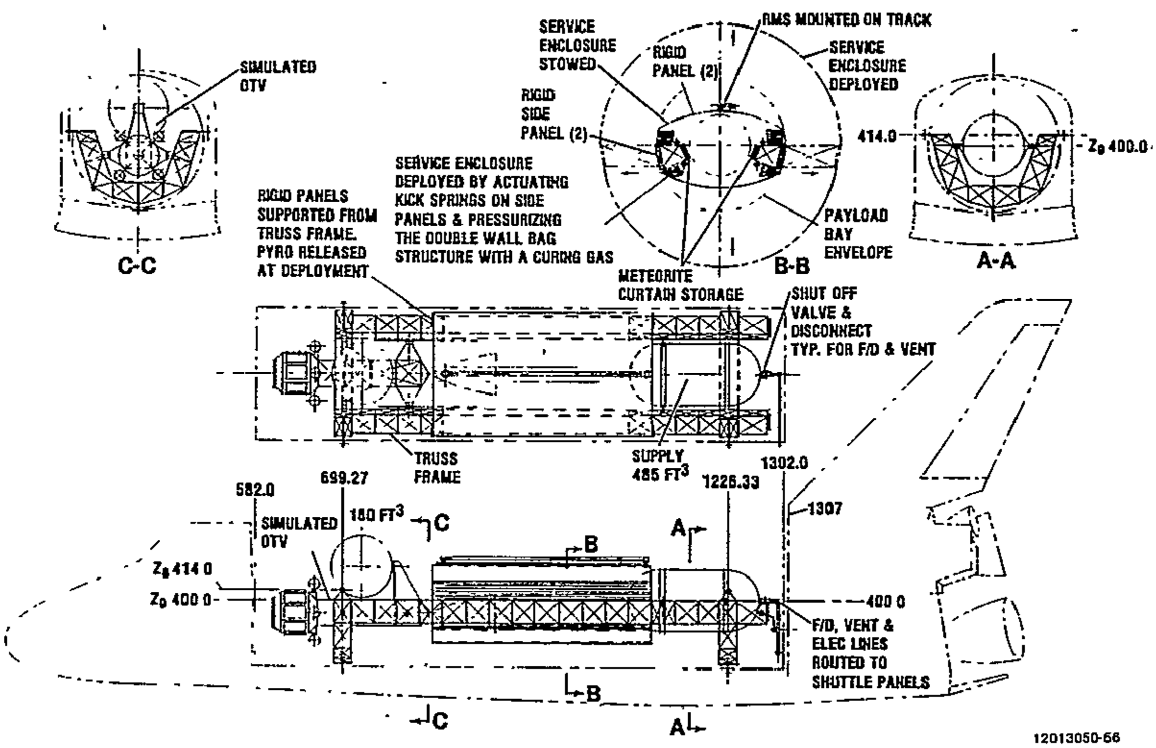

Figure 8-1 Combined TDM

All the same functions that were performed on the individual TDMs can be performed on the combined TDM in the same manner.

This approach has the advantage of reducing the costs of Shuttle launches for the TDMs. However, the disadvantage is that all the equipment must be ready to be launched at the same time. This approach was eliminated in favor of launching TDMs individually with other required Space Station payloads.

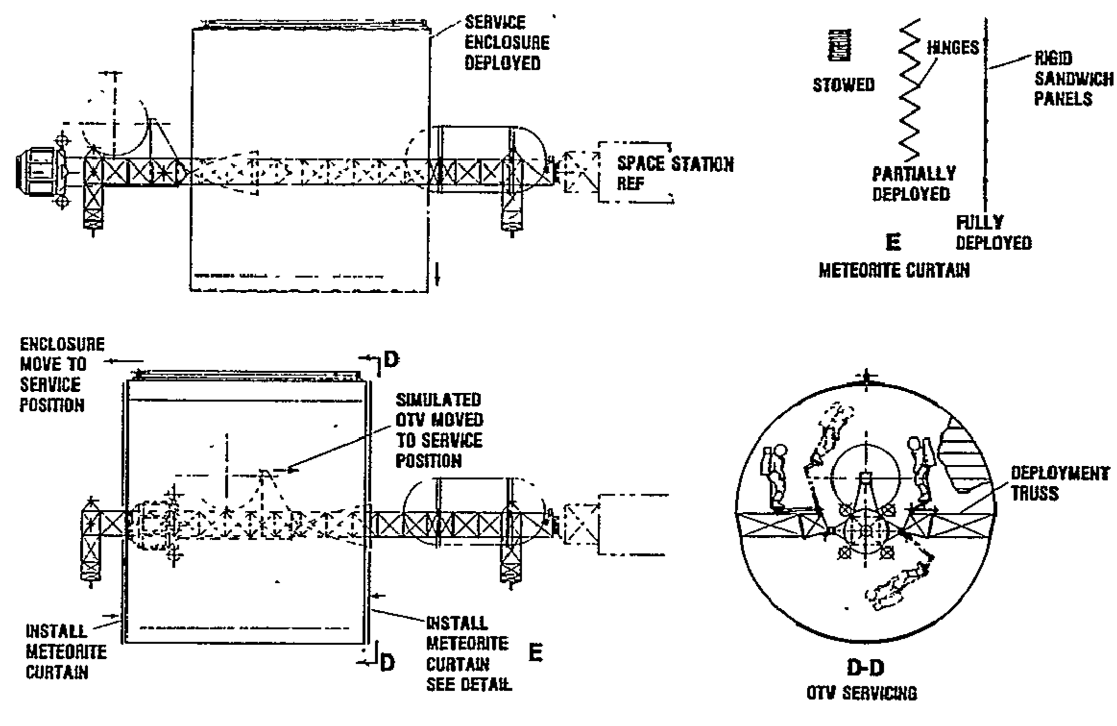

Figure 8-2 Combined TDM Orbit Operations

9.0 PROGRAMMATIC ANALYSIS

The objectives of this task are to provide the necessary plans, schedules and cost analysis to support the system/subsystem level trade studies and the definition of the Technology Development Mission(s). These objectives were accomplished by performing these two subtasks: (1) Plans and Schedules and (2) Cost Analysis. The results of these tasks are presented in the following sections.

9.1 PLANS AND SCHEDULES

Plan and schedule analysis deals with areas related to operational aspects of a program and those that concentrate upon the program development definition of the selected approach. The operational aspects of the TDMs at the Space Station have been addressed in previous sections. This section addresses the program development definition of the selected TDMs.

The evolutionary technology development plans have been presented for each of the selected TDMs. They indicate the functions to be tested and where these tests should be conducted, namely on the ground, in a Shuttle sortie mission and on the Space Station. The following figures indicate the time frame for those tests in order to efficiently develop the OTV servicing capability.

Figure 9-1 is the development schedule for the Propellant Transfer/Conservation TDM. The launch is proposed for 1 January 1991. Also shown are the recommended ground testing activities and the manifested and proposed Shuttle sortie missions to be performed in support of this TDM. We propose that a propellant transfer sortie mission similar to the one GD defined in Contract 3-321935 for NASA LeRC or the proposed Cryogenic Fluid Management Facility sortie mission along with the proposed MSFC Large Scale Cryogenic Storage Facility Flight Demonstration mission be flown in the time period shown to support the development of the TDM.

For reference, a possible development schedule for a space-based OTV (with a 1994 IOC) is shown to indicate how the TDM data can support its development. The TDM will essentially be the flight test verification during C/D of the approach in this area of the space-based OTV.

Shown on Figure 9-2 is the development schedule for the Docking, Berthing and Maintenance TDMs. Since the two TDMs use much of the same equipment, the two are developed together with the launch of the Docking and Berthing TDM occurring on 1 April 1991, and the launch of the Maintenance Enclosure on 1 June 1991. Shown also are the recommended ground testing activities and the manifested and proposed Shuttle sortie missions to be performed in support of the TDMs. We propose that missions involving EVA, automated remove/replace/handling, and zero leak fluid quick disconnect activities be performed to support the PDR of the TDM.

For reference, a possible development schedule for a space-based OTV (with a 1994 IOC) is shown to indicate how the TDM data supports its development. As was the case for the previous TDM, these TDMs will essentially be flight test verification during C/D of the approach in the area of the space-based OTV.

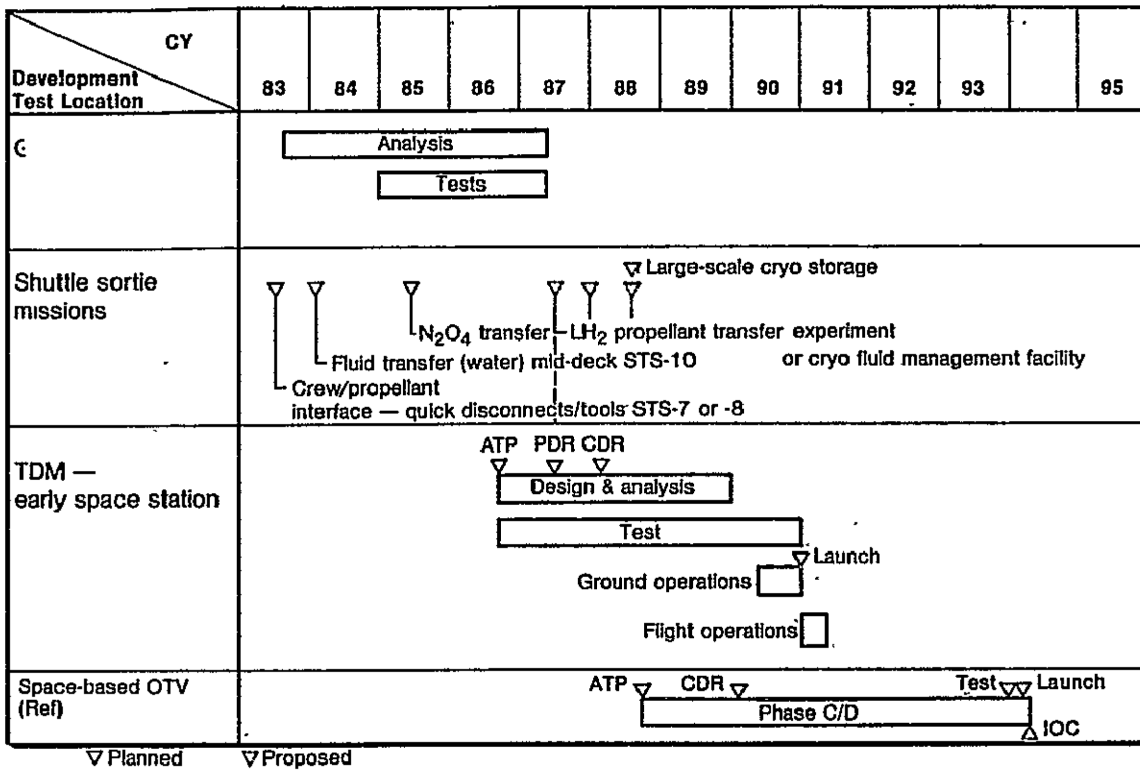

Figure 9-1 Propellant Transfer, Storage & Reliquefaction Technology Development Plan

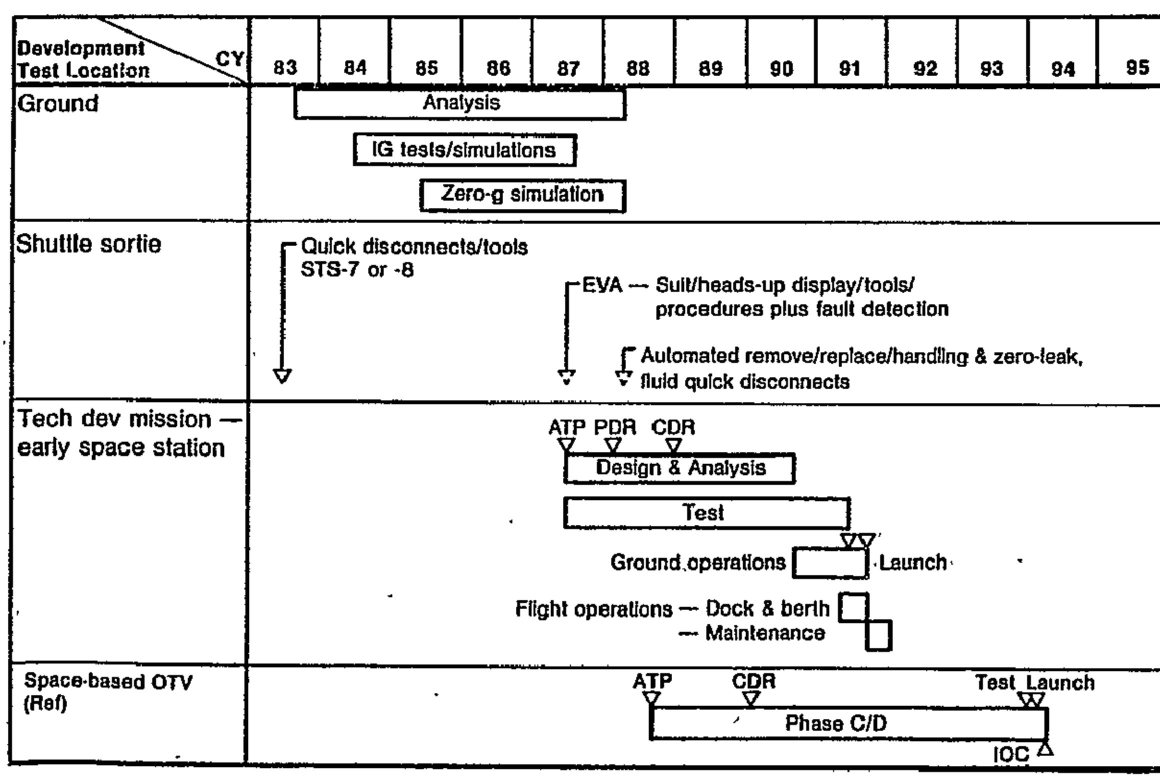

Figure 9-2 Docking, Berthing & Maintenance Technology Development Plan

In fact, some of the equipment used in the TDM could be engineering models of the space-based OTV components.

As stated before, the equipment for the OTV/Payload integration TDM is assumed to be at the Space Station and since the capability to perform the mission will be developed for the Maintenance TDM, a separate development plan is not required.

In this phase of the study, we could only concentrate on the development tests to be performed on the initial Space Station. In the follow-on phase, there is a task to generate an integrated technology development plan for the ground, sortie mission, and Space Station tests. This will allow us to better define the evolution of the recommended tests. However, in order to develop the OTV servicing capability in a timely manner, technology development work should be initiated immediately in the areas we have indicated.

9.2 COST ANALYSIS

A cost analysis of the Orbit Transfer Vehicle Servicing Technology Development Missions has been conducted and the results are presented herein. This section includes the Work Breakdown Structure, cost analysis methodology, ground rules and assumptions, and the program cost estimates themselves, including cost uncertainties and annual funding requirements.

These data represent preliminary top level estimates that can only reflect the program definition work performed to date and, therefore, cannot be considered complete or final. They do, however, represent a reasonable estimate based on information available at this time and are useful for planning purposes.

9.2.1 WORK BREAKDOWN STRUCTURE. The Work Breakdown Structure (WBS) is a comprehensive breakdown of all total program elements categorized or sorted into several levels of hardware and task or function-oriented end items. The resulting format is displayed for each major program phase, including project development, flight article production, and operational TDM flights. The WBS serves as the basic format for all cost reporting and programmatic data, and to organize, plan, and manage the subsequent program.

A preliminary WBS for the OTV Servicing TDM project is presented in Figure 9-3. The WBS is based on the final selected experiment concept hardware (Section 3.0 thru 6.0) and the program schedule and groundrules defined in Section 9.1 of this report.

The WBS serves to identify all of the cost elements to be included in the cost analysis task. This WBS contains all of the hardware and tasks associated with program Phase C/D development and test, the test hardware refurbishment and modification, and fabrication of the flight hardware, and the operations activities incurred during each TDM first flight.

The nonrecurring development portion of the C/D phase includes the one-time tasks and hardware to design and test the OTV Servicing TDM payloads. It includes the required design and analysis for all ground and flight hardware, including structural analysis, stress, dynamics, thermal, mass properties, etc. This phase also includes all software development. The nonrecurring

category includes component development and test through component qualification, as well as all component development test hardware. In addition, this phase includes: system engineering and integration; system-level test and refurbishment of the flight article using the protoflight approach; GSE design, development test, and manufacture; and lastly, overall program management and administration.

The production portion of the C/D phase (unit cost estimate) includes all tasks and hardware necessary to provide one complete set of flight hardware equipment. It includes all material and component procurement, parts fabrication and hardware refurbishment, subassembly, and final assembly. In addition, this category includes the required quality control/inspection task, an acceptance test procedure for sell-off to the customer, and program management and administration activities accomplished during the manufacturing phase.

Cost of the operations phase of the OTV Servicing TDM project, including Shuttle operations and mission operations such as tracking and data acquisitions (TDRSS), have not been addressed at this time.

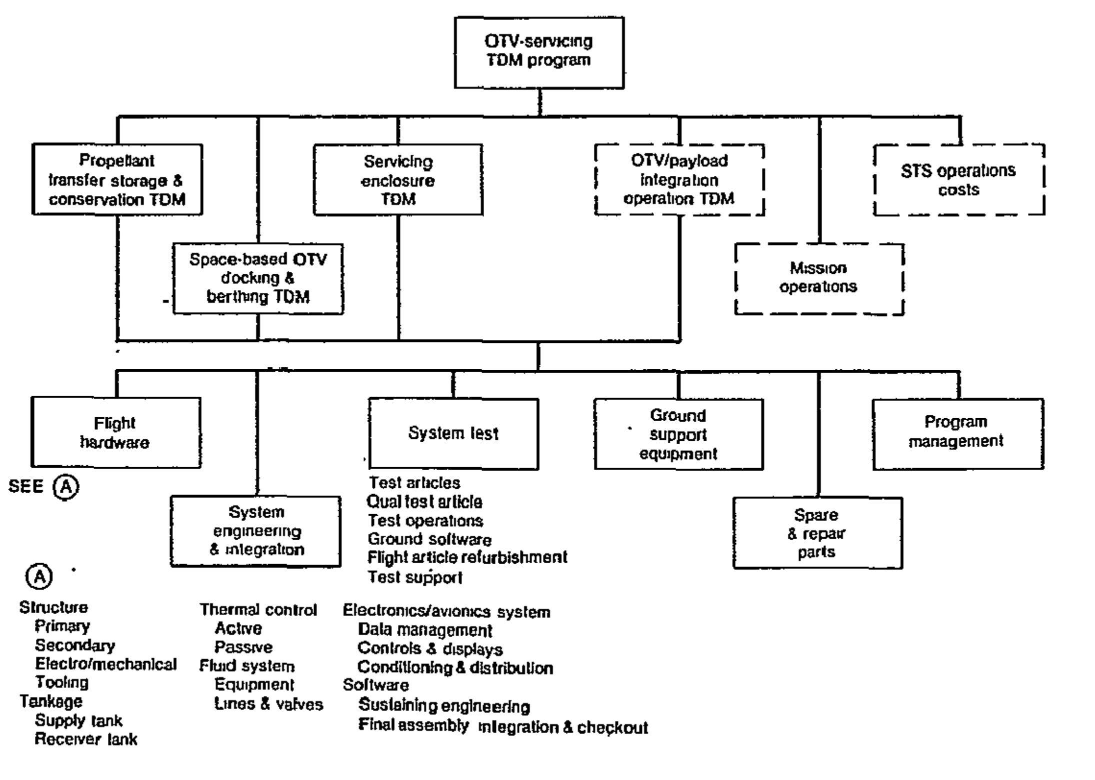

Figure 9-3 OTV Servicing Technology Definition Missions WBS

9.2.2 COST METHODOLOGY. A cost work breakdown structure was developed (Section 9.2.1) that includes all elements, chargeable to the Orbit Transfer Vehicle Servicing Technology Development Missions project for each of the program phases, i.e., development, production, and operations. This cost WBS sets the format for the estimating model, the individual cost estimating relationships (CERs), cost factors or specific point estimate requirements, and, finally, the cost estimate output itself. Cost estimates are made for each element, either at the WBS breakdown level shown or one level below in certain cases. These estimates are accumulated according to the WBS to provide the required development, flight article production, and first flight operations costs.

The estimating methodology varies with the cost element and with the availability of historical data or vendor quotes. For new non-off-the-shelf hardware, parametric CERs are used. These CERs were developed during past cost analysis activities performed by Convair on space experiment systems. These CERs have been derived for various categories of hardware and many subcategories representing differing levels of complexity or technology families. These CERs are derived from available historical cost data or detailed estimating information and relate cost to a specific driving parameter such as weight, area, power output, etc. For example, the various facility structural mechanical items, mechanisms, control systems, etc., were estimated using such CERs. The tankage for this experiment represents a special problem since little or no historical cost experience is available for this type of flight experiment, i.e., a set of equipment that will not be operational in the sense of a launch vehicle stage, yet still needs to meet the requirements and criteria necessary to fly in the Shuttle. Figure 9-4 shows a plot of cryogenic tankage cost vs. volume for three levels of technology complexity. These technology familes are 1) uninsulated tanks,

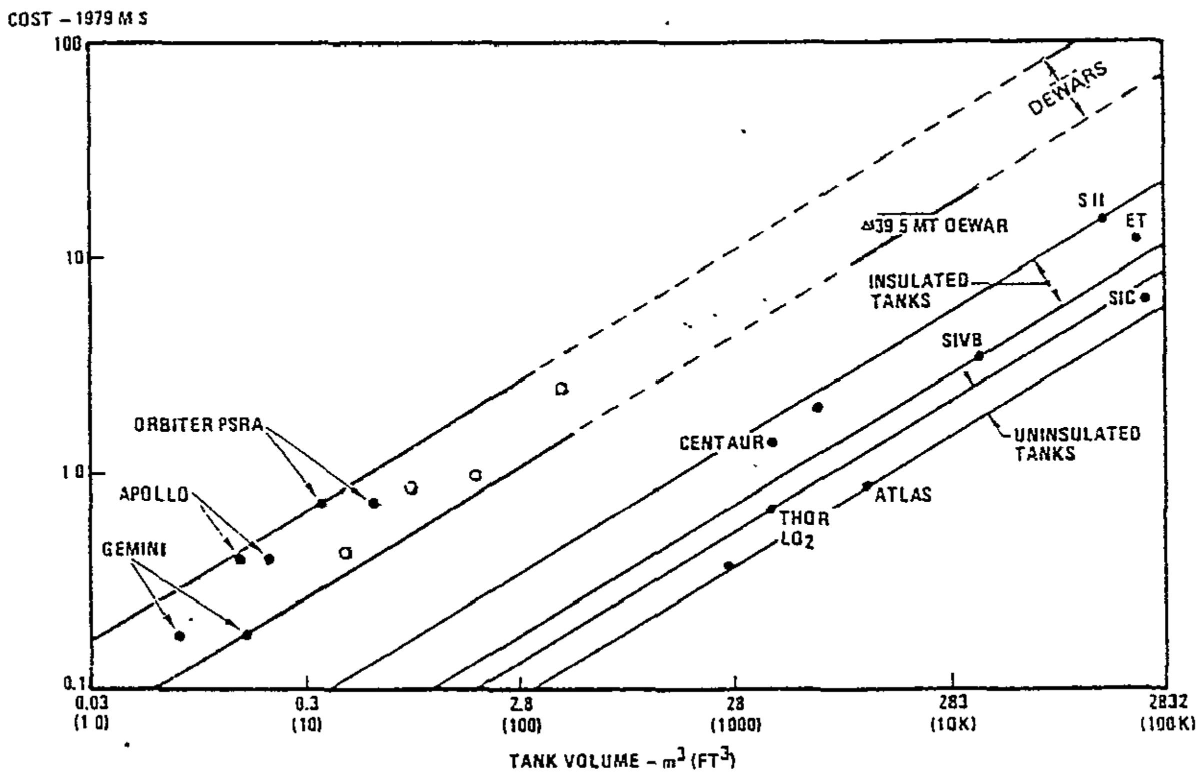

Figure 9-4 Cryogenic Tankage First Unit Cost Relationship

2) insulated tanks, and 3) vacuum insulated devices. It should be noted that all data points shown represent operational programs, not an experiment as considered in this study. It may be expected the cost impact of being "an experiment" will be substantial in the development phase cost but not necessarily too significant in the unit cost.

Hardware actual costs are shown with solid dots and estimates with open dots. They include the dewar family, a group of insulated tanks (mostly foam insulation) and a family of uninsulated tanks. Regressions for these three families produced nearly identical slopes. Uncertainty bands at a fixed average slope were then used to bound each family. As may be seen insulated tanks represent a factor of about 2.2 of the cost of uninsulated versions. A deficiency in this data is that the dewar data does not overlap that of the other tank data for the volume parameter and therefore cannot provide a positive confirmation of the average slope used.

Non-recurring or development cost data are shown in Figure 9-5. Less data were readily available than for unit costs and also more difficult to interpret because of the widely varying design requirements and development environments and philosophies. With respect to these development costs historical data suggest that development and qualification costs may run as high as 25 times the Theoretical First Unit (TFU) production cost for users having stringent design requirements, and ranging down to 5 times the TFU for relaxed requirements in the areas of weight, reusability, safety factor, etc. In fact, in cases with no weight limitations and very high safety factors, development may be equal to or even less than unit fabrication costs. This would represent a high degree of qualification by analysis and similarity, and minimum testing. The multiplication 5 x and 25 x development cost lines have been included in the figure for reference.

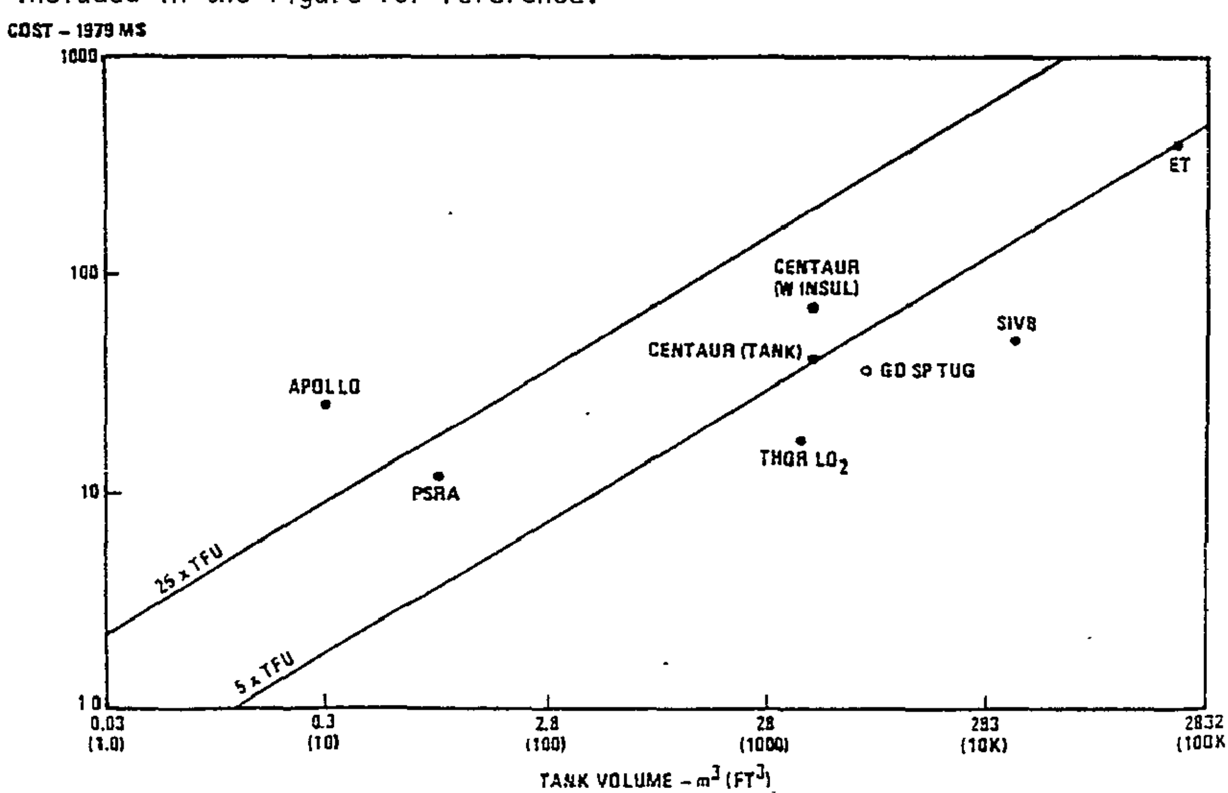

Figure 9-5 Cryogenic Tankage Development Cost Relationship

The conclusion from these data is that both development and unit production costs of these cryogenic tankages will be strongly dependent upon the design requirements imposed. As a result, specific assumptions need be made concerning each individual concept application. Information obtained since the initial analysis indicates that dewar cost may indeed be less than indicated if design requirements are relaxed from the applications shown. The judgment made at this time is that the tank unit fabrication costs are assumed to be 2.5 times the unit cost for the supply and receiver tanks. In the case of the receiver tank, the requirements and hence the design are quite close to flight weight tankage so as to obtain proper scaling of the resulting experiment data.

The remaining "floating item" cost elements such as system engineering and integration program management, etc., are estimated using simple cost factors consisting of appropriate percentages of the applicable related program effort.

9.2.3 <u>GROUND RULES AND ASSUMPTIONS</u>. The following general ground rules and assumptions were used in estimating the costs presented herein.

a. Costs are estimated in current/constant FY 1983 dollars.

b. No prime contractor fee is included in these estimates.

c. The costs include all facility payload-related costs incurred from the start of Phase C/D (development phase) through a single (first) launch of each TDM.

d. No new facilities will be required chargeable to the OTV Servicing TDM program.

e. All system level development and qualification testing is conducted using the flight article which is refurbished prior to flight.

f. NASA IMS and Program Office costs are excluded.

g. STS operations costs are excluded.

h. TDM flight operations costs are not addressed at this time.

i. These cost data are Rough Order of Magnitude and for planning purposes only.

9.2.4 COST ESTIMATE. The resulting ROM cost estimates for the three Technology Development Missions are summarized in Table 9-1 through Table 9-3. The estimates are given in constant FY 1983 millions of dollars and exclude prime contractor fee. The hardware estimates identify costs for both component development (design, modification, test article procurement) and component test and qualification. Costs shown include software, Ground Support Equipment (GSE), and initial spares. Other wrap-around costs include facility-level design and analysis, system engineering and integration, facility level testing, and project management. Operations costs and post-flight maintenance and refurbishment costs have been excluded in this estimate, as well as reflights and payload updates or modifications.

As may be seen, Propellant Transfer/Conservation TDM hardware (component) development is expected to cost \$35.2 M, and the flight hardware production and/or procurement cost is estimated at \$10.7 M. The remaining cost elements bring the development and flight unit costs to \$49.2 and \$11.2 M, respectively, for a total acquisition cost for this TDM of \$60.4 M.

Similarly, hardware development for the Docking and Berthing TDM is estimated to cost \$14.8 M, with production cost estimated at \$6.7 M. Wrap-around cost elements bring the development and unit costs to \$22.2 M and \$7.4 M, for a total acquisition cost of \$29.6 M.

Flight vehicle hardware development and production costs for the Maintenance Enclosure TDM are estimated at \$8.3 M and \$3.2 M, respectively. Including the other cost elements, development costs sum to \$11.7 M and flight unit costs to \$3.4 M, for a total acquisition cost of \$15.1 M.

Table 9-1 Cost Estimate
Propellant Transfer/Conservation TDM

	Cost (FY83 \$M) Development	Flight Unit
Flight vehicle hardware	35.2	10.7
Propellant transfer/storage	25.4	8.0
Reliquefaction	9.8	2.7
System engineering & integration	3.5	
System test & evaluation	4.9	
Ground support equipment	1.8	
Spares	1.5	
Program management	2.3	0.5
Total	49.2	11.2
TDM total	60.4	

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Table 9-2 Cost Estimate
Docking & Berthing TDM

	Cost (FY83 $M)	
	Development	**Flight Unit**
Flight vehicle hardware	14.8	7.1
System engineering & integration	1.5	
System test & evaluation	3.2	
Ground support equipment	0.7	
Spares	0.9	
Program management	1.1	0.3
Total	22.2	7.4
TDM total	29.6	

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Table 9-3 Cost Estimate
Maintenance TDM

	Cost (FY83 $M)	
	Development	**Flight Unit**
Flight vehicle hardware	8.3	3.2
System engineering & integration	0.8	
System test & evaluation	1.5	
Ground support equipment	0.4	
Spares	0.1	
Program management	0.6	0.2
Total	11.7	3.4
TDM total	15.1	

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The OTV/Payload Integration TDM is assumed to have a zero delta development and unit cost at this time because of the assumptions indicated in Section 9.1

Total Orbit Transfer Vehicle Servicing Technology Definition Missions program nominal cost is then about $105 M. The confidence limits on this estimate are judged to have an uncertainty of about -10 percent to +20 percent, depending upon the design requirements imposed. These cost uncertainties are shown in Table 9-4. Total program cost may vary from about $95 M with eased design requirements to about $126 M with more stringent requirements imposed.

Annual funding requirements for each TDM are shown individually in Figure 9-6. These funding requirements were efficiently calculated using our computerized phased-funding model. Using the costs for each WBS element estimated (Figure 903) the model properly spreads the cost of each element over time in accordance with the program development as previously presented in Table 9-4, and automatically accumulates costs as desired. As may be seen, peak-year funding of $47.7 M occurs the year after the ATP (Authority to Proceed) on the initial TDM, the Propellant Transfer/Conservation TDM. Study groundrules place this peak-funding year at 1988. The slightly irregular funding profile for the Maintenance Enclosure TDM is due to the large amount of design commonality, thereby reducing the funding needed for development relative to production, and to scheduling variations.

Table 9-4 Cost Uncertainties

	Cost (FY 83 $M)		
	Low	Nominal	High
Propellant transfer/conservation TDM	**54.4**	**60.4**	**72.5**
• Development	44.3	49.2	59.1
• Flight article	10.1	11.2	13.4
Docking & berthing TDM	**26.6**	**29.6**	**35.5**
• Development	20.0	22.2	26.6
• Flight article	6.6	7.4	8.9
Maintenance enclosure TDM	**13.6**	**15.1**	**18.1**
• Development	10.5	11.7	14.0
• Flight article	3.1	3.4	4.1
Total program	**94.6**	**105.1**	**126.1**

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There wasn't time during the study to investigate the high cost components in each TDM to see if alternate approaches could be adopted to reduce the costs. For instance, the receiver tank in the Propellant Transfer TDM could also be an Engineering Test Model for the space-based OTV. As such, the total cost of developing and manufacturing it wouldn't have to be borne by the TDM. In the follow-on study phase, the high cost items will be analyzed to find methods to reduce their costs.

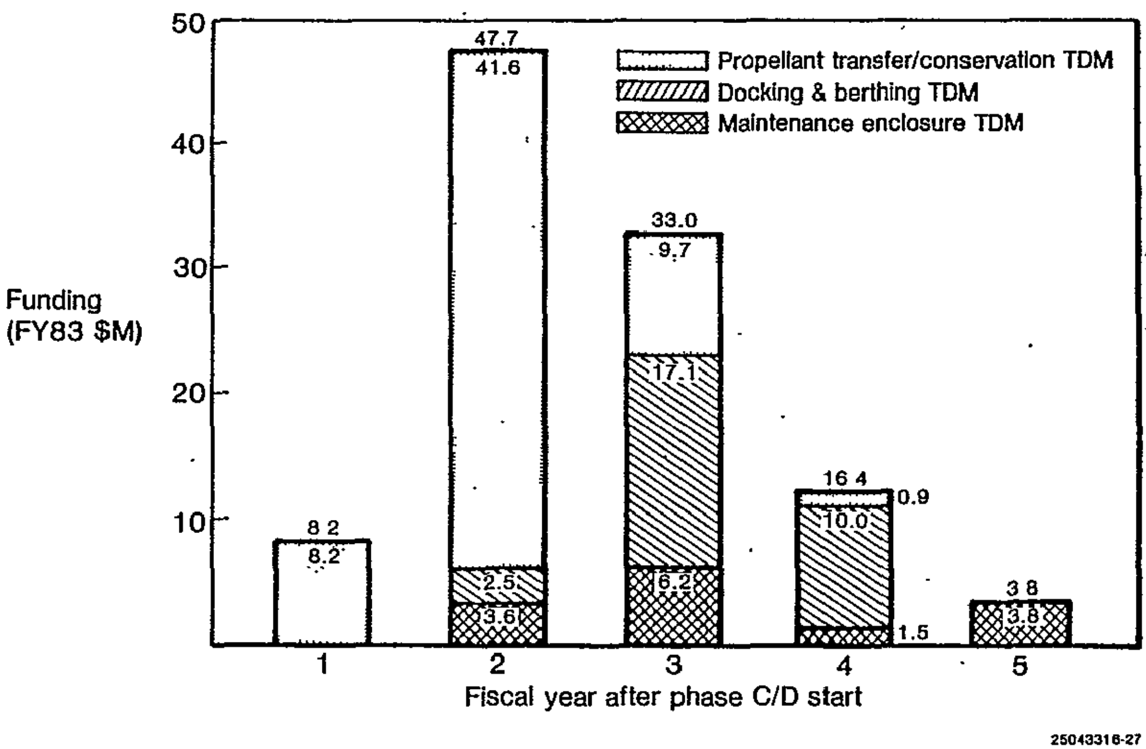

Figure 9-6 Cost Summary - Annual Funding Requirements Nominal Estimate

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10.0 TDM EQUIPMENT OPERATIONAL USAGE

Figure 10-1 shows a possible approach to making use of the TDM equipment for the OTV operational mission. Since the operational OTV is larger in diameter than the simulated OTV, the berthing maintenance bay must be made larger. The docking/berthing/maintenance TDM trusses can be detached from the propellant TDM trusses and attached to the Space Station to provide another bay for additional tanks. Two or more TDM tanks can be delivered to the Space Station to meet the operational OTV capacity. The maintenance enclosure can be enlarged to the required diameter by adding four panels.

The concept has not been studied in any depth in this phase of the study but will be addressed in the follow-on to determine the optimum approach for use of the TDM equipment.

There are a variety of other possible uses for the TDM propellant tanks other than being used as part of the operational OTV missions. Different size tanks and other arrangements may be more effective for the OTV operational mission. Figure 10-2 lists several viable uses for these tanks. Certainly, if one of these applications is the chosen ultimate use for the tanks, then a slightly different capacity may be appropriate.

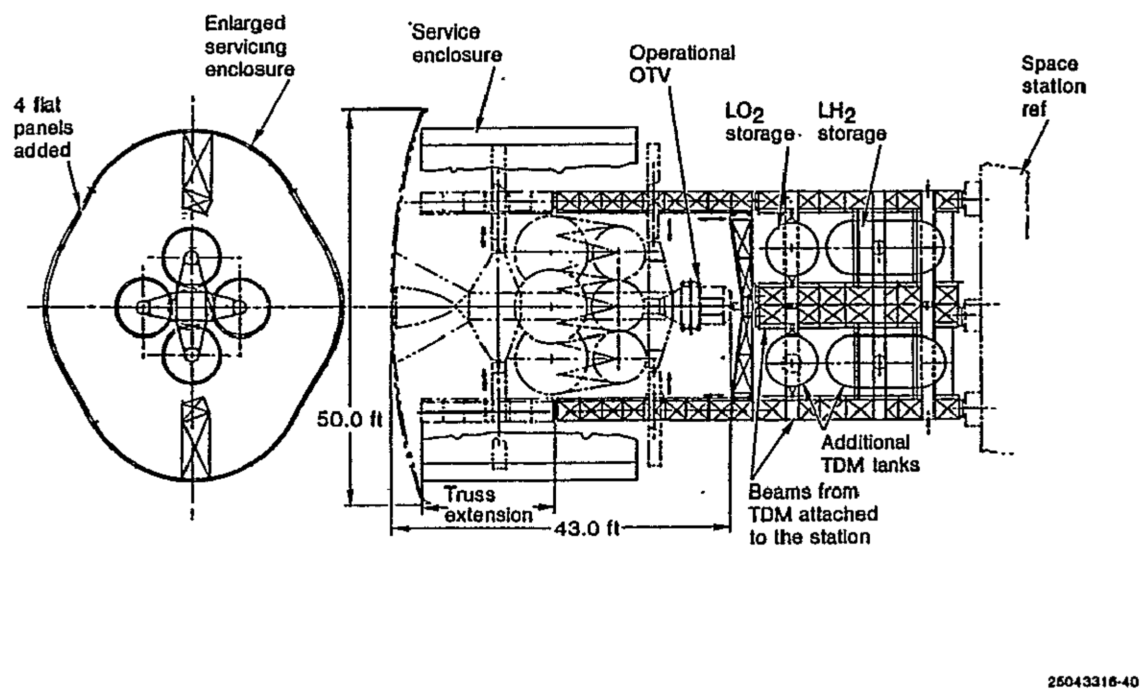

Figure10-1 Potential TDM Growth to Support Operational Missions

- Source of supply for topping off early ground-based OTVs at the station
- Source of supply for fuel cell subsystems used as backup or augmentation to space station principal power supply
- Possible supply for space-based cryogenic TMS (supercritical propellant), which would eliminate contamination problem
- Propellant supply for space station cryogenic RCS
- Source of supply of cryogenic fluids for superconducting magnets, coolant for sensors, etc

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Figure 10-2 Alternative Usage for TDM Propellant Tanks

11.0 CONCLUSIONS AND RECOMMENDATIONS

11.1 CONCLUSIONS

The study conclusions are summarized as follows:

- TDMs that develop/demonstrate the capability to support a space-based OTV are required on the initial space station in the areas of
  - Propellant transfer, storage & reliquefaction
  - Docking & berthing
  - Maintenance
  - OTV/payload integration
- Greater understanding of the space station functions required to support an operational space-based OTV is needed to finalize TDMs
- Integrated technology development plan is needed to focus ground, shuttle sortie & early space stion TDMs
- Additional analysis is needed to better understand the TDMs & their impact on the initial space station

Our study has shown, through the operations/functional analysis and evolutionary technology development plan for needed OTV servicing capabilities tasks, that there are requirements to perform TDMs in the four areas shown above. However, there was only time to do a very preliminary analysis of the space station functions required to support an operational space-based OTV. We feel that the basic functions have been identified but that additional work in more depth must be accomplished to finalize the requirements for the TDMs.

In the evolutionary technology development plan task, the study approach called for emphasis on identifying the test requirements for the initial space station and there wasn't time to identify the test requirements for the ground and sortie mission modes to the same depth. As a consequence, an integrated technology development plan has not been generated. This needs to be accomplished to optimize the tests required in each category and refine the TDMs.

With the funding and time available for this study, the definition of the TDMs is very preliminary. Additional analysis is needed to better understand the TDMs and their impact on the station, and make them more cost effective.

11.2 RECOMMENDATIONS

Recommendations for follow-on activity are as follows:

- Perform additional operational analyses to identify space station functions required to totally support an operational space-based OTV

- Determine capability of the initial space station to support/service an OTV (ground-based) for an early operational mission (1990-1992 time period)
- Generate integrated technology development plan
  - Ground
  - Sortie
  - Early space station
- Initiate required technology analytical tasks
- Initiate and/or update recommended sortie mission experiment definitions
- Continue definition studies for technology development mission for early space station

Most of these recommendations have been incorporated into the work statement for the follow-on phase to this contract. However, timely initiation of required technology analytical tasks to develop the OTV servicing capability and initiation and/or update of recommended Shuttle sortie missions to support this development needs to be accomplished outside of the follow-on contract by the appropriate NASA technology managers.

12.0 REFERENCES

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APPENDICES

A. FUNCTIONAL FLOW DIAGRAMS

Lower level functional diagrams than presented in the body of the report.

B. END-TO-END OPERATIONS CHARTS

More detailed functional flows, timelines and operations data for the TDMs than shown in the body of the report

Figure A-7 R/R AVIONICS MODULE — REMOTE CONTROLLED ARM (RCA)

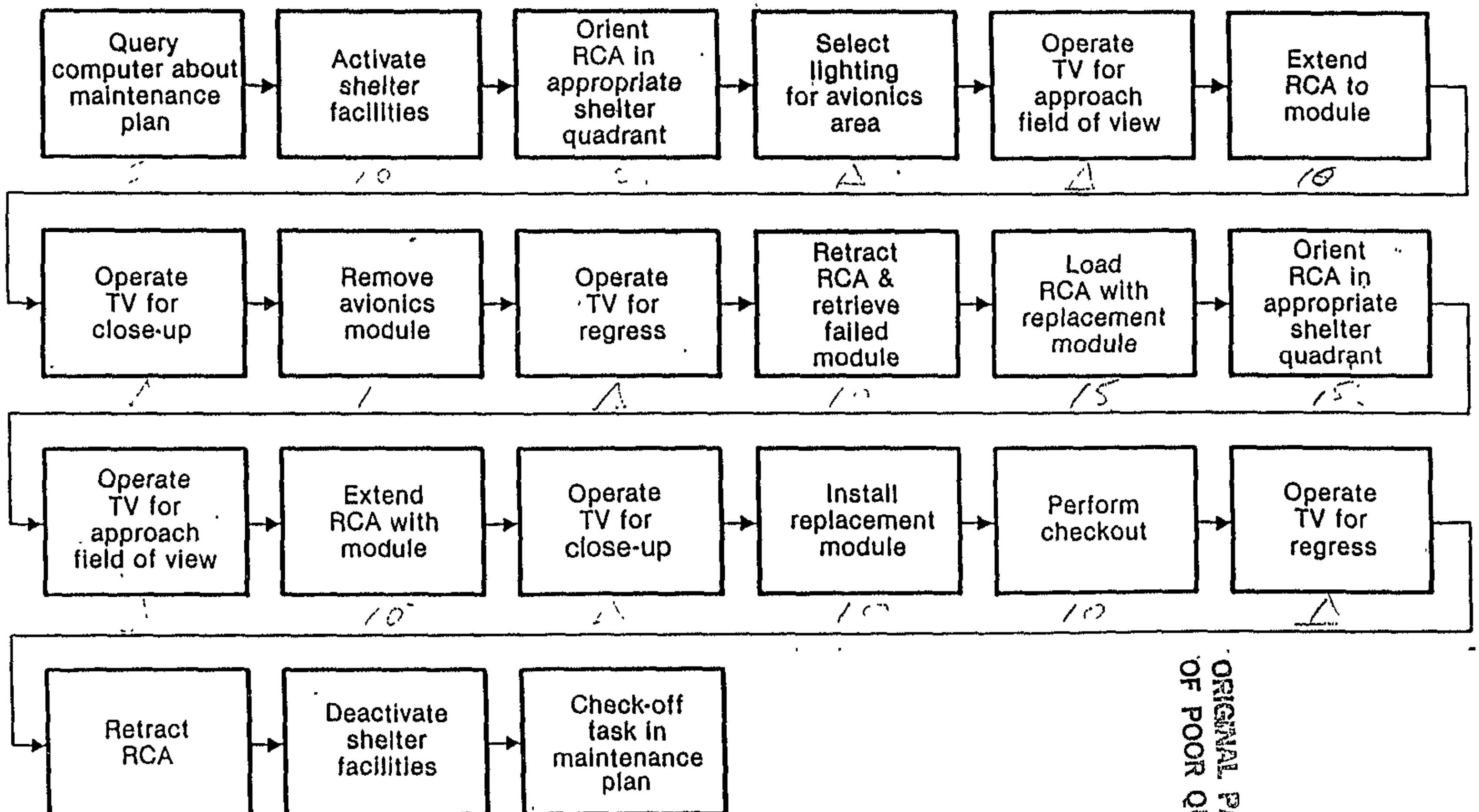

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Figure A-3 R/R ENGINE-EVA OPERATION

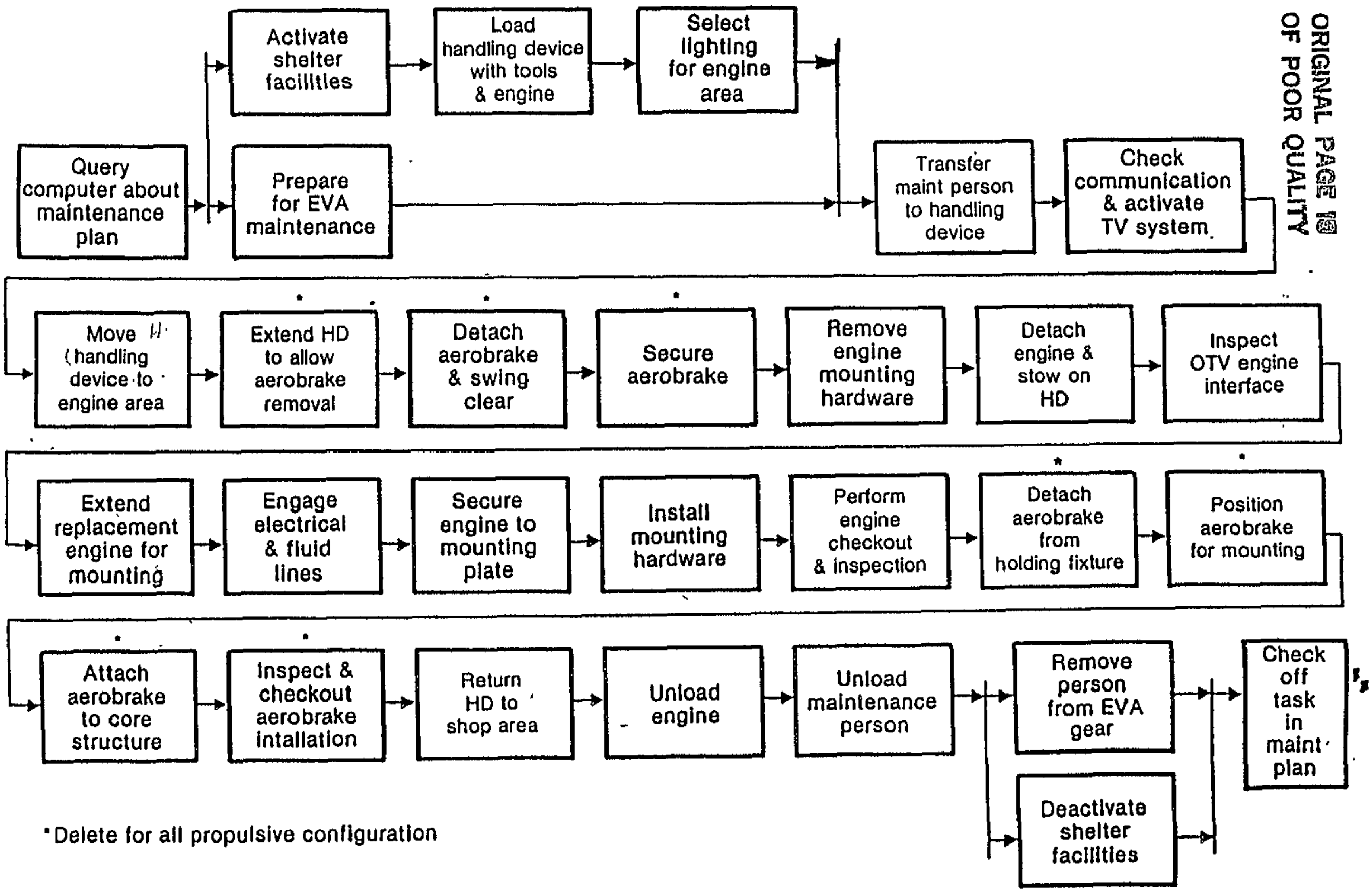

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Figure B-1 DOCKING & BERTHING TDM OPERATIONS

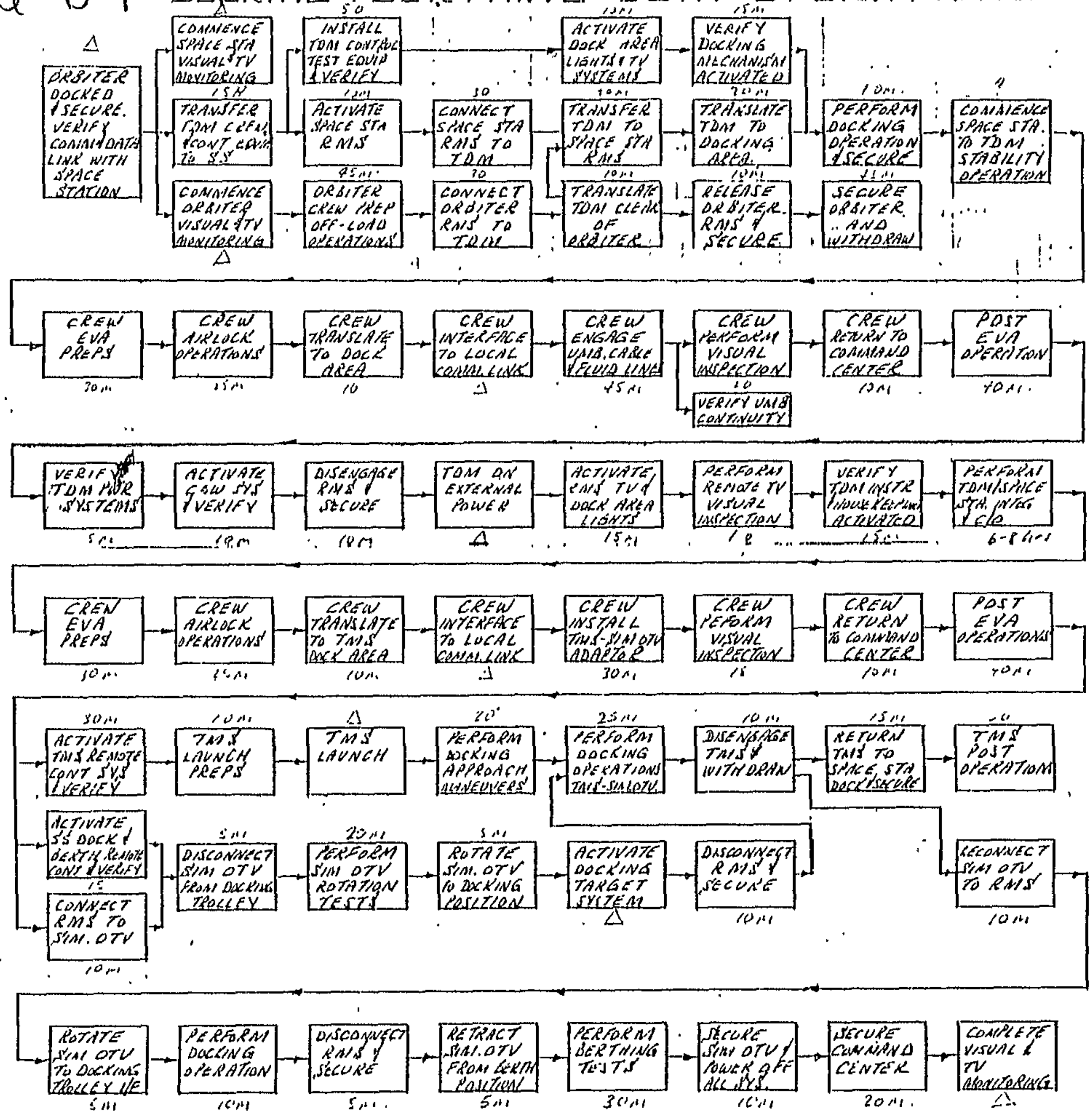

Figure B-2

DOCKING & BERTHING TDM OPERATIONS

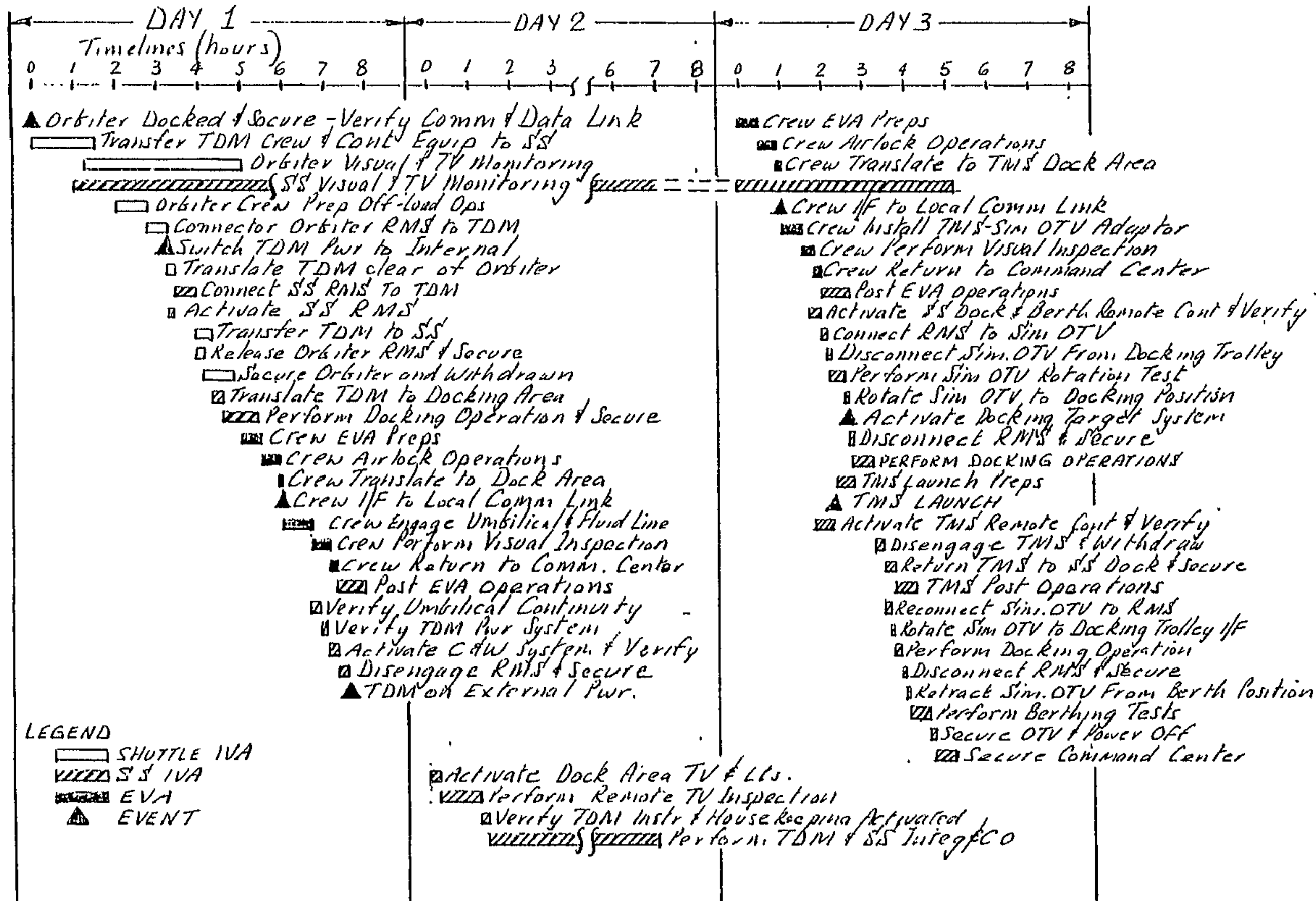

Figure B-3

SERVICING ENCLOSURE OPERATIONS

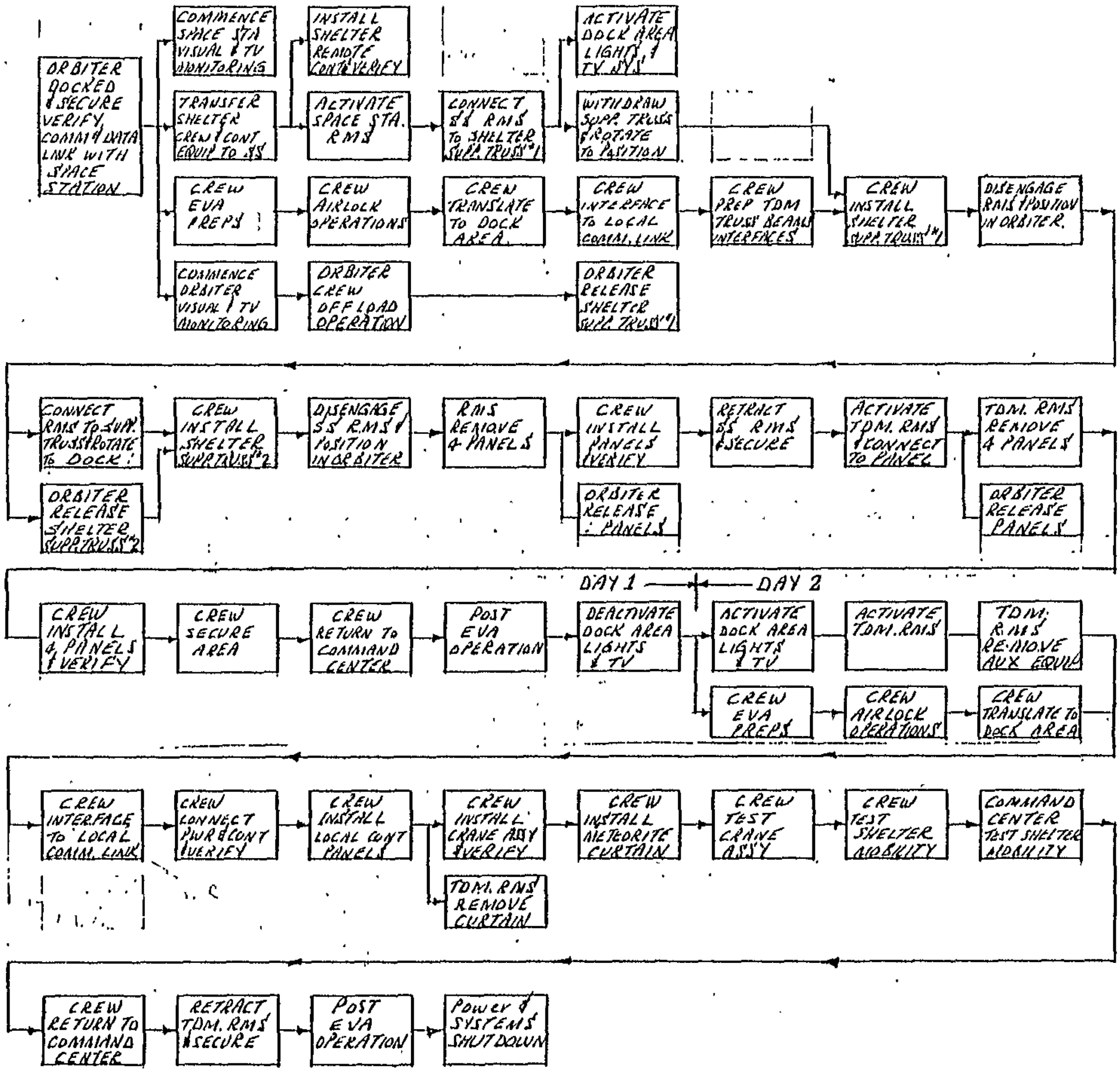

Figure B-4

SERVICING ENCLOSURE TDM OPERATIONS

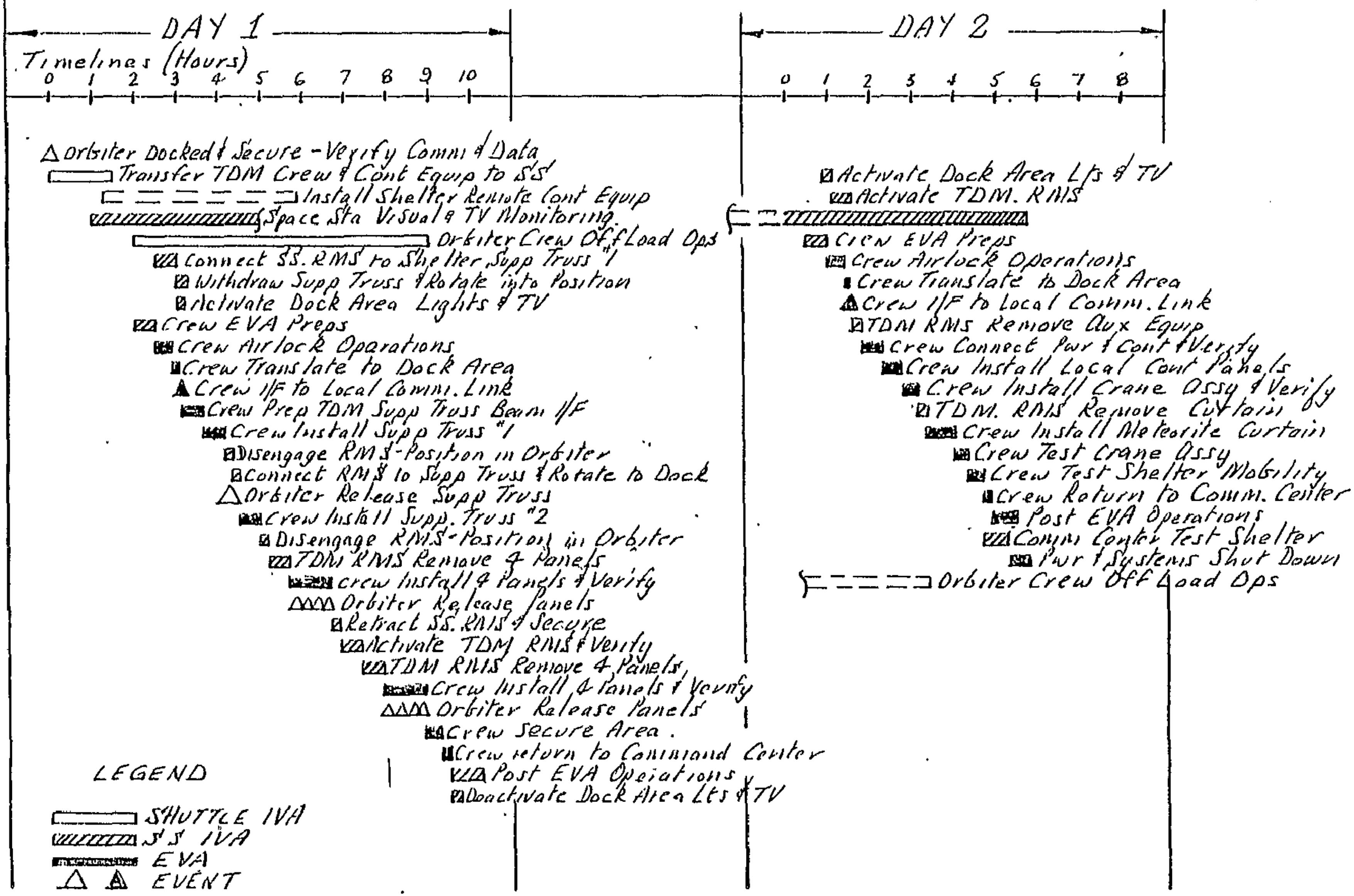

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Figure B-5

AVIONICS MODULE-SERVICE/MAINTENANCE OPS

REPLACEABLE UNITS

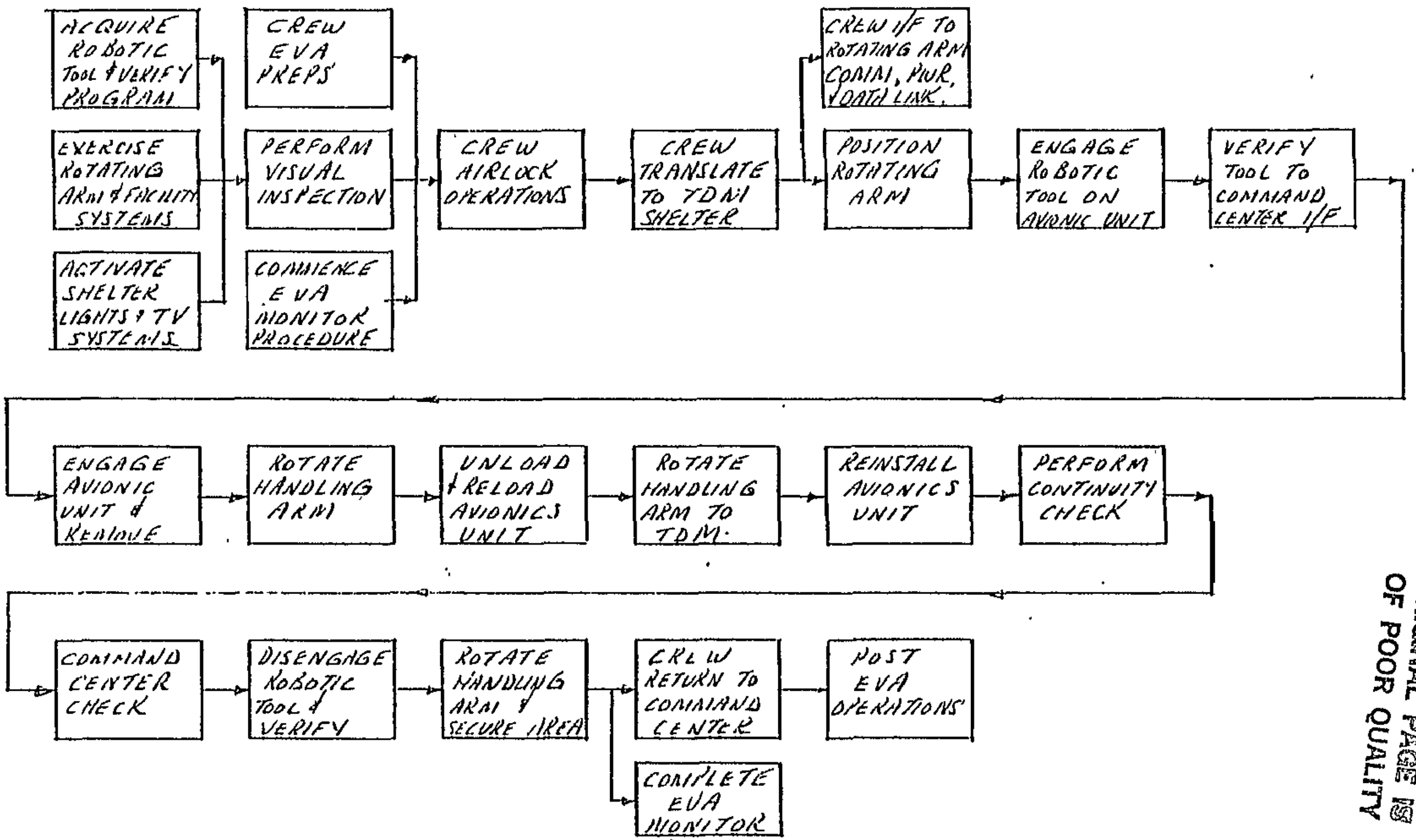

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Figure B-6

AVIONICS MODULE ~ SERVICE/MAINTENANCE
REMOVE/REPLACE UNIT

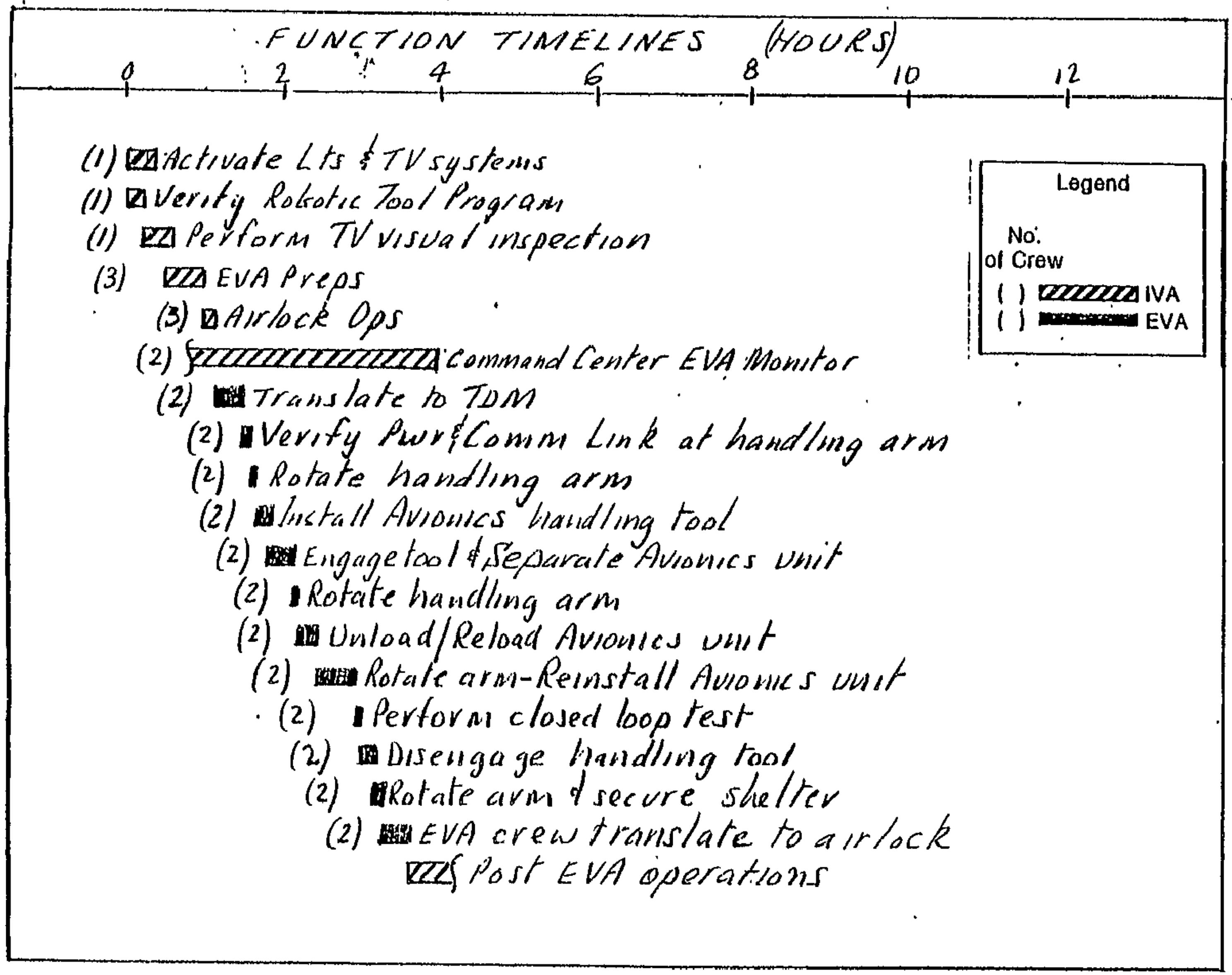

Figure B-7

TDM MAINTENANCE SUMMARY - AVIONICS MODULE

FUNCTIONAL REQUIREMENTS	EQUIVALENT GROUND TASK	SPACE STATION TDM TASK	IVA	EVA	SUPPORT EQUIP REQUIREMENTS	COMMENTS
SERVICING — AVIONICS MODULE UNITS						
PREPARATIONS:		•REVIEW SIM FLT [illegible]				
		•VERIFY SHELTER IN POS'N	✓			
•PREPARE TDM SHELTER	•INSTALL WORK PLATFORM	•ACTIVATE SHELTER LTS & TV SYS ON.	✓		REMOTE CONTROL TV	
	•VERIFY POWER OFF	•EXERCISE ROTATING ARM	✓			
•CREW EVA	•ACQUIRE REPLACEMENT UNIT(S)	•CREW EVA PREPS	✓		EMU & SPACE TOOLS	
•ACQUIRE AVIONIC UNIT HANDLING TOOL	•ACQUIRE TOOLS	•COMMAND CENTER COMMENCE EVA MONITOR	✓		SEMI-ROBOTIC AVIONIC UNIT HANDLING TOOL (1)	(1) MODULAR UNITS WILL BE COMPATIBLE WITH TOOL OPERATED BY CREWMAN OR REMOTE CONTROL
•TRANSLATE CREW TO TDM SHELTER		•CREW EGRESS AIRLOCK & MOVE TO TDM		✓		
•ESTABLISH COMM, TV & DATA LINK TO COMMAND CENTER	•CONNECT COMM. LINK TO BLOCKHOUSE	•CONNECT CREW I/F TO PWR & COMM LINKS ON CHERRY PICKER & VERIFY	✓	✓ ✓	HARDLINE I/F & LINK ON CHERRY PICKER TO COMMAND CENTER.	
REMOVAL & REPLACEMENT OPERATIONS:						
•DISCONNECT ELECT UMBILICAL (2)	•REMOVE ELECT HARNESS(S)	•INSTALL ROBOTIC TOOL ON ROTATING ARM		✓		(2) ANTICIPATE ELECT UMBILICAL CONNECTION TO BE INCORPORATED INTO FASTNER PLATE.
		•POSITION ROTATING ARM	✓	✓		
		•ENGAGE TOOL ON AVIONIC UNIT.		✓		
•SEPARATE SELECTED MOCKUP AVIONICS UNIT FROM AVIONICS MODULE. (3)	•DISENGAGE FASTNERS & REMOVE UNIT.	•VERIFY TOOL ON REMOTE CONTROL	✓		COMPUTER PROGRAM	(3) SIMULATED UNIT WILL HIGH FIDELITY MOCKUP EXTERNALLY. ALSO CONTAIN INTERNAL LOOP ACROSS CONNECTOR PINS
		•DISENGAGE UNIT & ROTATE CHERRY PICKER (4)		✓		
•SIMULATE TRANSFER TO & FROM STORAGE REMOVED & REPLACEMENT UNIT.	•MOVE UNIT TO STORAGE.	•UNLOAD & RELOAD AVIONICS UNIT		✓		
		•ROTATE CHERRY PICKER	✓	✓		(4) AVIONIC UNITS WILL HAVE STANDARDIZED FASTNERS AND CONNECTOR TYPES
•REINSTALL MOCK AVIONICS UNIT. (5)	•ENGAGE FASTNERS & HARNESS(S)	•POSITION TOOL & RENGAGE FASTNERS		✓		
•PERFORM SIMULATED FUNCTION TEST	•PERFORM CHECKOUT & FUNCTION TEST.	•PERFORM CLOSED LOOP VERIFICATION TEST.	✓		READOUT FUNCTION IN COMMAND CENTER.	
•STORE AVIONICS HANDLING TOOL (ALSO REFERRED TO AS ROBOTIC TOOL)	•REMOVE TOOLS & SECURE AREA.	•DISENGAGE ROBOTIC TOOL		✓		(5) AVIONICS UNIT WILL SIMULATE BOTH REMOVE & REPLACEMENT UNITS
		•ROTATE CP & SECURE AREA.	✓	✓		
		•CREW RETURN TO COMMAND CENTER	✓	✓		
		•POST EVA				

Figure D-8 CORE SECTION—SERVICE MAINTENANCE OPERATIONS
BATTERY AND FUEL CELLS

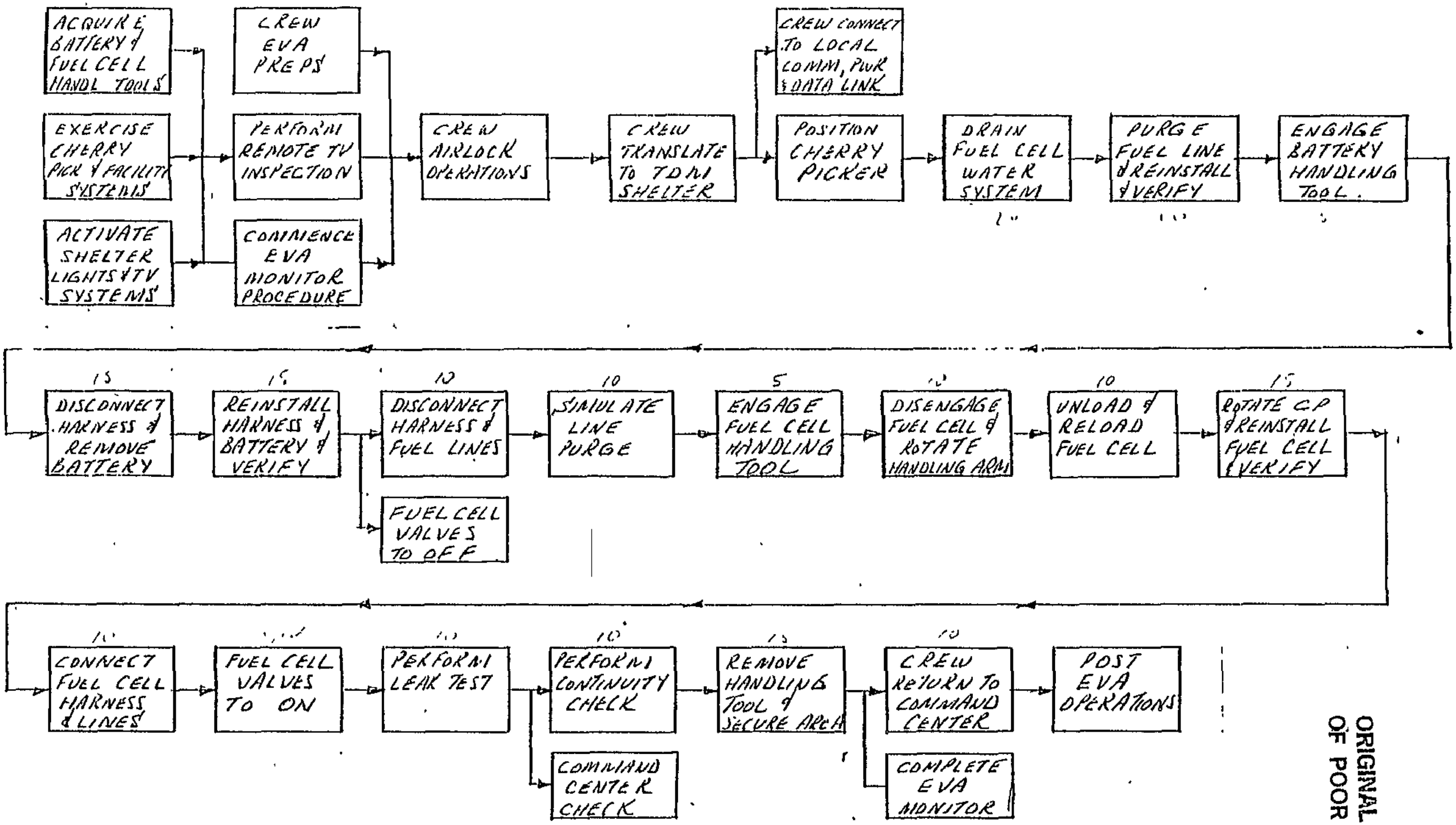

Figure B-9 CORE SECTION - SERVICE/MAINTENANCE BATTERY & FUEL CELLS

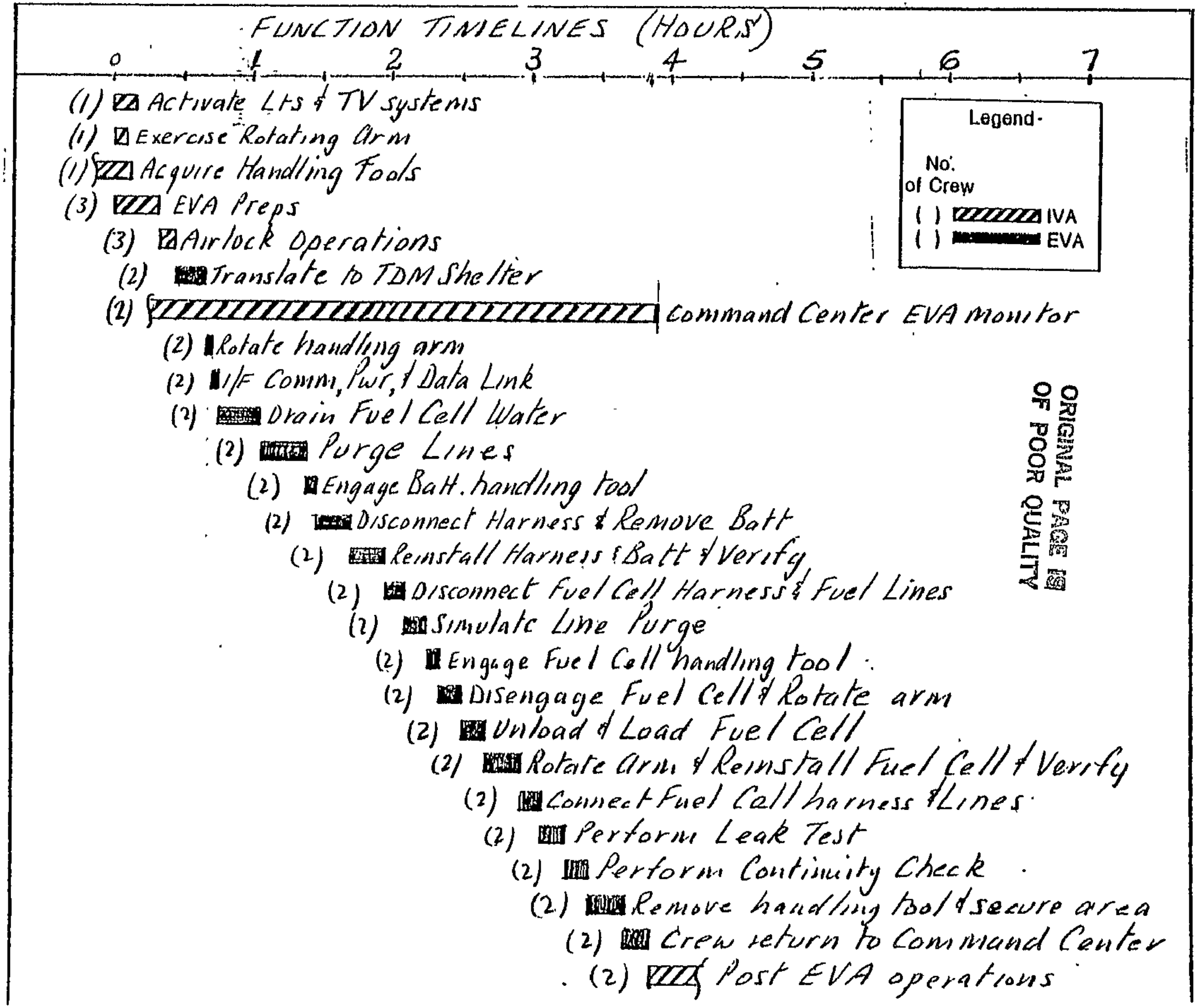

Figure B-10 TDM MAINTENANCE SUMMARY ~ CORE SECTION

FUNCTIONAL REQUIREMENTS	EQUIVALENT GROUND TASK	SPACE STATION TDM TASK	IVA	EVA	SUPPORT EQUIP. REQUIREMENTS	COMMENTS
SERVICING PREPARATIONS. FUEL CELLS SYSTEM • PREPARE TDM SHELTER.	• INSTALL WORK PLATFORM • VERIFY POWER OFF	• PLACE SHELTER IN POSITION • ACTIVATE SHELTER LTS & TV SYS ON • EXERCISE TDM CHERRY PICKER	✓ ✓ ✓			(1) TDM FUEL CELL & BATT. MOCKUP UNITS WILL SIMULATE BOTH REMOVE & REPLACEMENT UNITS
• CREW EVA	• ACQUIRE TOOLS & REPLACEMENT UNITS (1)	• CREW EVA PREPS (5) • COMMAND CENTER COMMENCE EVA MONITOR	✓ ✓		EVA TYPE HAND TOOLS	
• VISUAL INSPECTION	• PERFORM VISUAL INSPECT	• PERFORM TV INSPECTION	✓		REMOTE CONTROL TV SYS	
• TRANSLATE CREW TO TDM		• CREW EGRESS AIRLOCK & TRANSLATE TO TDM AREA				
• ESTABLISH COMM, TV & DATA LINK TO COMMAND CENTER	• CONNECT COMM LINK TO BLOCKHOUSE	• CONNECT CREW I/F TO PWR & COMM LINKS ON HANDLING ARM. & VERIFY	✓	✓	COMM. LINK & PWR SUPPLY PANELS LOCATED THRU TDM & SHELTER AREAS	
SERVICE OPERATIONS						
• FUEL CELL WASTE MANAGEMENT & PURGE	• DISCONNECT RADIATOR & DRAIN WATER. • PURGE FUEL LINES & REINSTALL	• POSITION CHERRY PICKER • DRAIN WATER (2) • PURGE SIMUL. FUEL LINE & REINSTALL/VERIFY.		✓ ✓ ✓	NITROGEN SUPPLY	(2) HIGH FIDELITY VALVE REQUIRED FOR PURGE OPERATION
• REMOVE AND REPLACE BATTERY (1)(3)	• DISCONNECT HARNESS & REMOVE BATTERY • INSTALL NEW BATTERY & OLD BATT TO STORAGE	• ENGAGE BATT HANDLING TOOL • DISCONNECT CABLE & REMOVE BATTERY • REINSTALL CABLE AND BATTERY & VERIFY		✓ ✓ ✓	BATTERY HANDLING TOOL	(3) SIMULATE BATTERY MASS, WEIGHT & HARNESS INTERCONNECTS
• REMOVE AND REPLACE FUEL CELL (1)(4)	• INSPECT • VALVES TO OFF • DISCONNECT HARNESS & FUEL LINES • PURGE LINES • REMOVE FUEL CELL • INSTALL NEW CELL • CONNECT FUEL LINES & HARNESS	• INSPECT (6) • VALVES TO OFF • DISCONNECT HARNESS & FUEL LINES • SIMULATE LINE PURGE • INSTALL FUEL HANDLING TOOL • DISENGAGE FUEL CELL • UNLOAD & RELOAD FUEL CELL • MOVE C.P AND REINSTALL FUEL CELL & VERIFY. • CONNECT HARNESS & LINES • VALVES TO ON		✓ ✓ ✓ ✓ ✓	HELMET HEADUP DISPLAY (6) HARNESS & FLUID LINE HANDLING TOOLS. FUEL CELL HANDLING TOOL	(4) SIMULATE FUEL CELL MASS, WEIGHT, HARNESS & FLUID LINES. CONNECTORS WILL BE HIGH FIDELITY. (5) ASSUME HAND TOOLS ARE STORED IN COMMAND CENTER & TDM MODULE HANDLING TOOLS ARE LOCATED AND STORED ON APPROPRIATE TDM STRUCTURE.
• LEAK AND FUNCTION TEST	• PERFORM LEAK TEST • PERFORM CONTINUITY & FUNCTION TEST. • REMOVE TOOLS AND SECURE AREA.	• PERFORM LEAK TEST/INSPECT • PERFORM CONTINUITY TEST • REMOVE HANDLING TOOL & SECURE AREA • CREW RETURN TO COMMAND CENTER • POST EVA	✓ ✓	✓ ✓	READOUT FUNCTION IN COMMAND CENTER.	(6) PERFORMED USING EVA HELMET HEAD UP DISPLAY & CAMERA ALSO BUDDY SYSTEM

Figure B-11

HYDRAZINE (ACS) BOTTLE SERVICING EVALUATION

SPACE STATION IMPACT	BOTTLE REFILL	BOTTLE REPLACEMENT
FACILITIES	• COMPLEX STORAGE & [illegible] SYS • MULTIPLE DETECTION [illegible] SYS • NITROGEN SUPPLY OR LEAKPROOF [illegible] • WATER DILUTION SYSTEM. • ISOLATION TBD DISTANCE • TEMPERATURE SENSITIVE ENCLOSURE • COMPLEX PLUMBING • SPECIALIZED RACKS	• STANDARD STORAGE [illegible] • SIMPLE SNIFFER SYS • BOTTLES PRESSURIZED • NITROGEN SUPPLY NOT REQUIRED. • ISOLATION TBD • MINIMUM ENVIRONMENT SHELTER • NO PLUMBING REQUIRED. • SPECIALIZED RACKS
SUPPORT EQUIPMENT	• GLASS LINED OR STAIN. STEEL STORAGE TANK • REMOTE CONTROL LOADING SYS. • LEAK TEST EQUIPMENT • SPECIAL TOOLS • COMPLEX HANDLING	• LEAK TEST EQUIPMENT. • STANDARD HANDLING
LOGISTICS	• REPLACE HYDRAZINE & WATER REQUIRES SCHEDULED MISSION MANIFEST LOADING. • SHUTTLE CANNOT PERFORM DIRECT TANKING OPERATIONS WITH HYDRAZINE. • MINIMUM RESUPPLY MISSIONS • EXPANDS SPACE STATION SELF SUPPORT ROLE	• USE CARGO EXCESS VOLUME • BOTTLES 5 YEAR FULLY STORABLE.
OPERATIONS	• REFILL ANY SIZE BOTTLE • REDUCES BOTTLE INVENTORY • COMPLEX REFILL PROCEDURE • BOTTLE DRAIN CAPABILITY. • REQUIRES BOTTLE IGNITION UNIT LEAK TEST • INCREASED IVA-EVA OPERATIONS • VACUUM REFILL IS NEW TECHNOLOGY.	• BOTTLES PRESSURIZED/SHOCK RESISTANT. • POTENTIAL LARGE INVENTORY. • BOTTLE READY TO GO • BOTTLE RETURNED TO EARTH. • LEAK TEST NOT REQUIRED • STANDARD REMOVE FROM STORAGE OPS. • LOW COMPLEXITY REPLACE OPERATION
SAFETY	• HIGHLY TOXIC HAZARD • HYDRAZINE REFILL HAZARD • HIGH ANTI-HAZARD REQUIREMENTS	LOW TOXIC HAZARD. • HYDRAZINE BOTTLE REPLACE SAFE
COST	• HIGH INITIAL COST. • RESUPPLY MAY CAUSE REVENUE LOSS	• LOW INITIAL COST • USE CARGO EXCESS VOLUME.

REDUCES/ELIMINATES NEED FOR PUMP ON OTV & SIMILAR VEHICLES

Figure B-12 PROPULSION – SERVICE/MAINTENANCE OPERATIONS

ATTITUDE CONTROL SYSTEM (ACS)

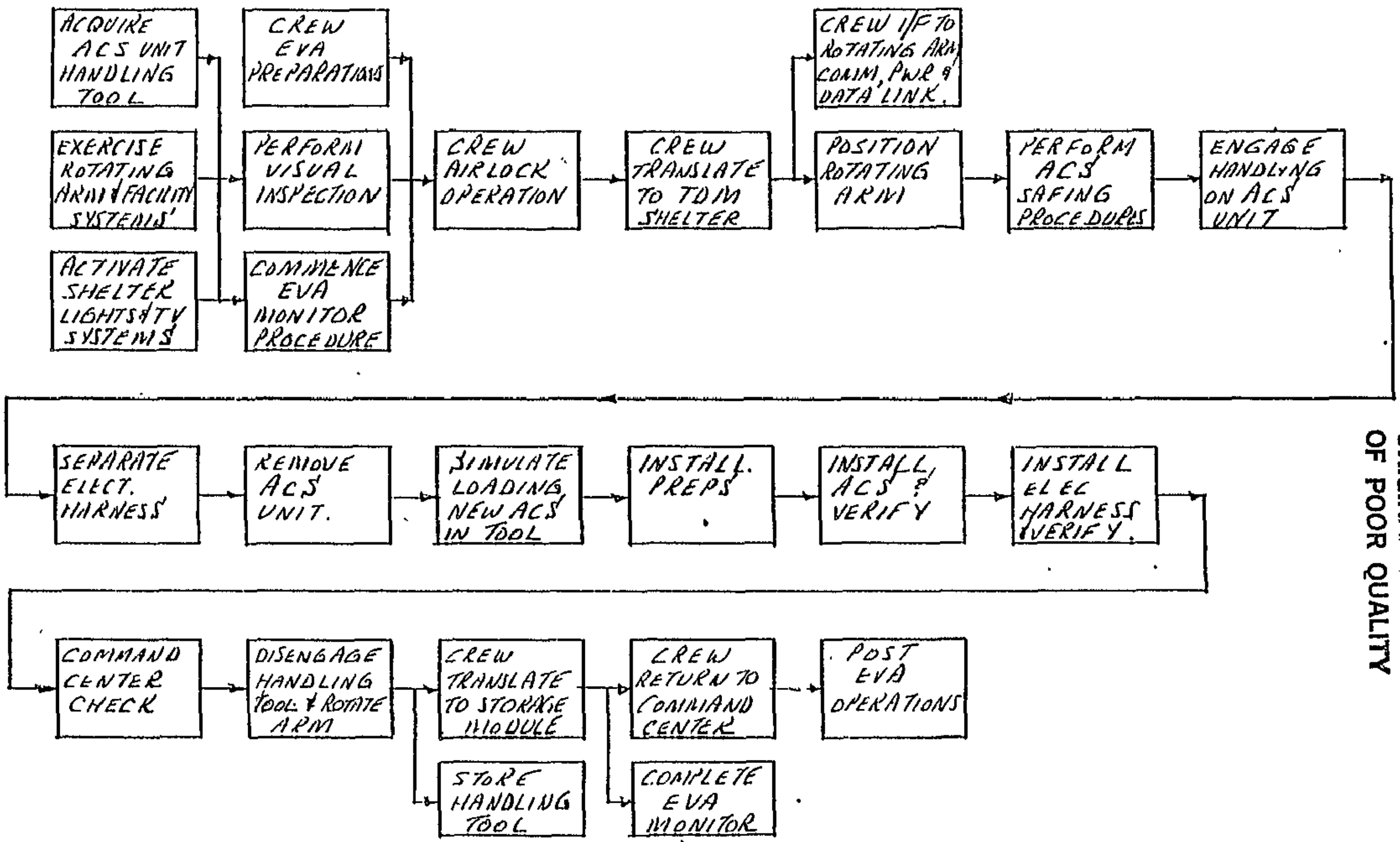

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Figure B-13 ACS UNITS – SERVICE/MAINTENANCE
Propulsion

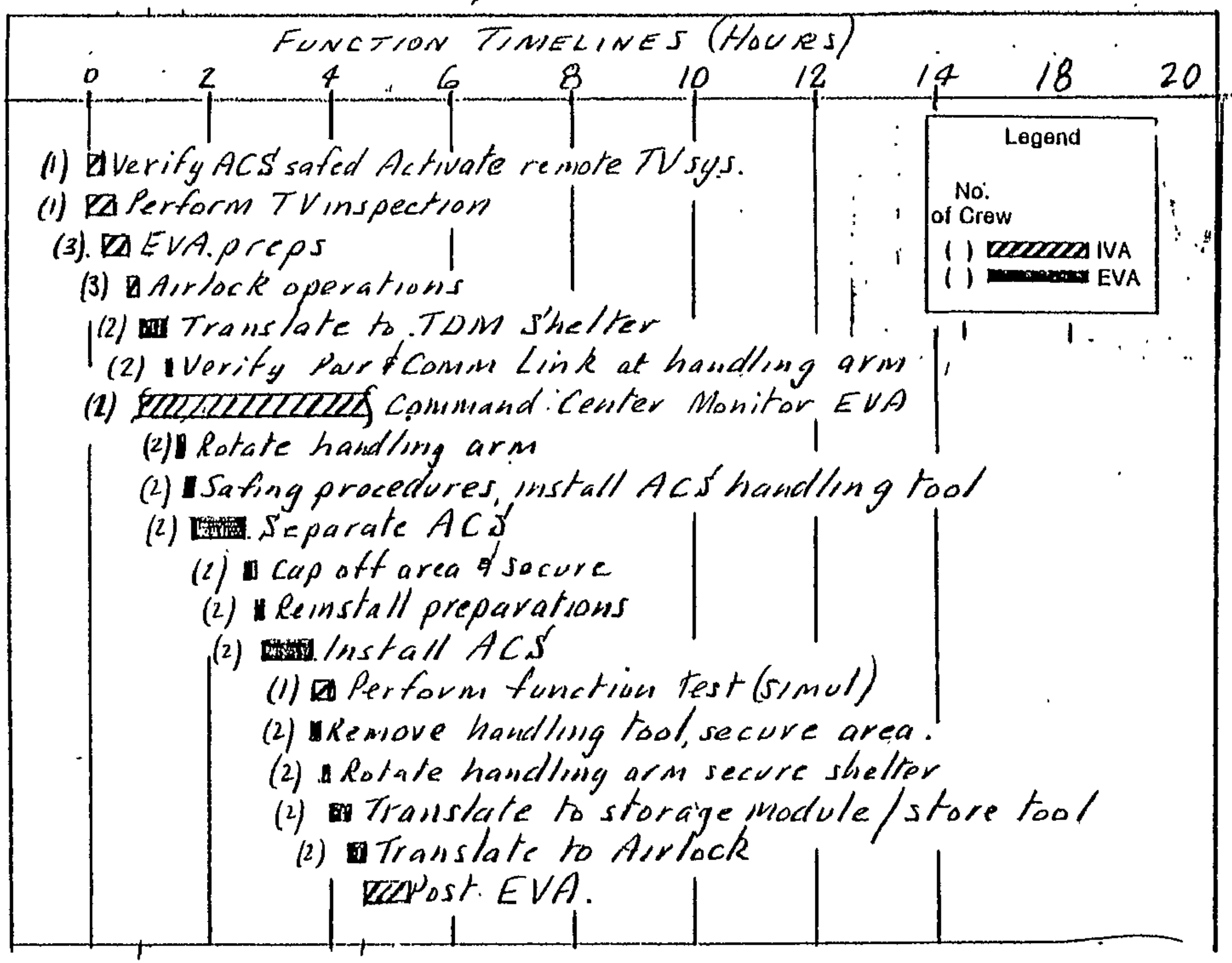


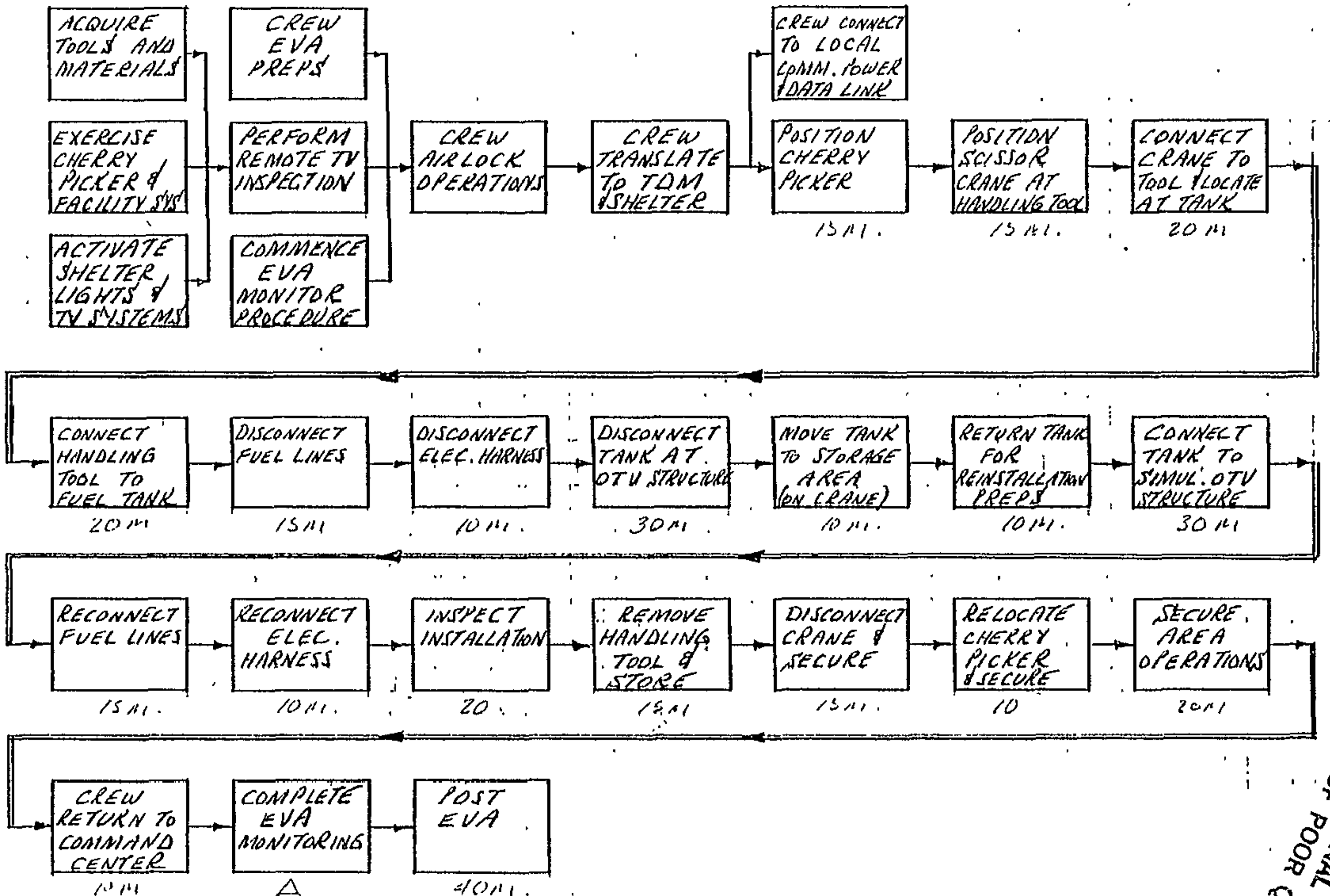
Figure B-14

TDM MAINTENANCE SUMMARY ~ PROPULSION

FUNCTIONAL REQUIREMENTS	EQUIVALENT GROUND TASK	SPACE STATION TDM TASK	IVA	EVA	SUPPORT EQUIP REQUIREMENTS	COMMENTS
SERVICING $\boxed{\text{ACS UNIT}}$ REMOVE AND REPLACE						(1) SIMULATED ACS WILL BE HIGH FIDELITY MOCKUP FOR ONE (1) UNIT ONLY.
PREPARATIONS		• VERIFY SHELTER IN POSITION	✓			
• PREPARE TDM SHELTER	• INSTALL WORK PLTFORM	• ACTIVATE SHELTER LTS & TV SYSTEM.	✓		• REMOTE TV SYS	
	• VENT AS REQUIRED	• CREW EVA PREP.	✓		• EMU & SPACE TOOLS	
• CREW EVA	• SAFE ACS	• CREW EGRESS AIRLOCK & MOVE TO TDM.	✓	✓		
• TRANSLATE CREW TO TDM SHELTER	• INSTALL SAFETY EQUIP.					
• ESTABLISH COMM & TV LINK TO CC & AVAILABILITY	• ESTABLISH COMM LINK	• CONNECT CREW I/F TO PWR & COMM LINK AT HANDLING ARM.		✓	• HARDLINE I/F LINK ON CHERRY PICKER TO COMM CENTER	
• SIMULATE REMOTE SAFING PROCEDURES	• PURGE AREA.					
• ACQUIRE ACS HANDLING TOOL	• ACQUIRE TOOLS	• COMMAND CENTER MONITOR EVA.	✓			(2) ELEC. HARNESS WILL SIMULATE CLOSED LOOP RESPONSES FOR FUNCTION TEST.
REMOVE/REPLACE OPERATIONS						
• DISCONNECT ACS UMBILICAL (2)	• SIMILAR	• VERIFY ACS SAFED	✓	✓		
• SEPARATE MOCKUP ACS FROM MODULAR RING UNIT. (1)	• SIMILAR	• INSTALL HANDLING TOOL & REMOVE ELEC. HARNESS		✓	• ACS TRANSPORTATION & HANDLING TOOL (3)	
		• SEPARATE ACS		✓	• TOOL(S) TO REMOVE ACS BOLTS & FASTNERS	
• SIMULATE TRANSFER TO/FROM ACS STORAGE	• SIMILAR.	• CAP OFF UMBILICAL				(3) ACS HANDLING TOOL CAPABLE OF ACS/TDM SEPARATION OPERATIONS
• REINSTALL ACS MOCKUP (1)	• INSTALL NEW UNIT. - CONNECT PLUMBING. - CONNECT ELEC HARNESS - ENGAGE FASTNERS & SECURE.	• REINSTALL ACS		✓		
		• REINSTALL HARNESS		✓		
		• PERFORM SIMULATED FUNCTION TEST.	✓			
• PERFORM FUNCTION TEST (SIMUL)	• PERFORM FUNCTION/CHECKOUT TEST.	• PERFORM LEAK SURVEY (OPTIONAL)		✓	• EMU GAS DETECTOR	
		• REMOVE HANDLING (3) TOOL & SECURE AREA		✓		
• STORE ACS HANDLING DEVICE.	• REMOVE TOOLS & SECURE AREA	• MOVE HANDLING TOOL TO STORAGE AREA.		✓	• STORAGE RACKS	
		• CREW RETURN TO COMMAND CENTER	✓	✓		
		• POST EVA.				

Figure B-15

TANK CHANGEOUT-SERVICE MAINTENANCE OPERATIONS



B-15

Figure B-16

TANK CHANGEOUT ~ SERVICE MAINTENANCE OPERATIONS

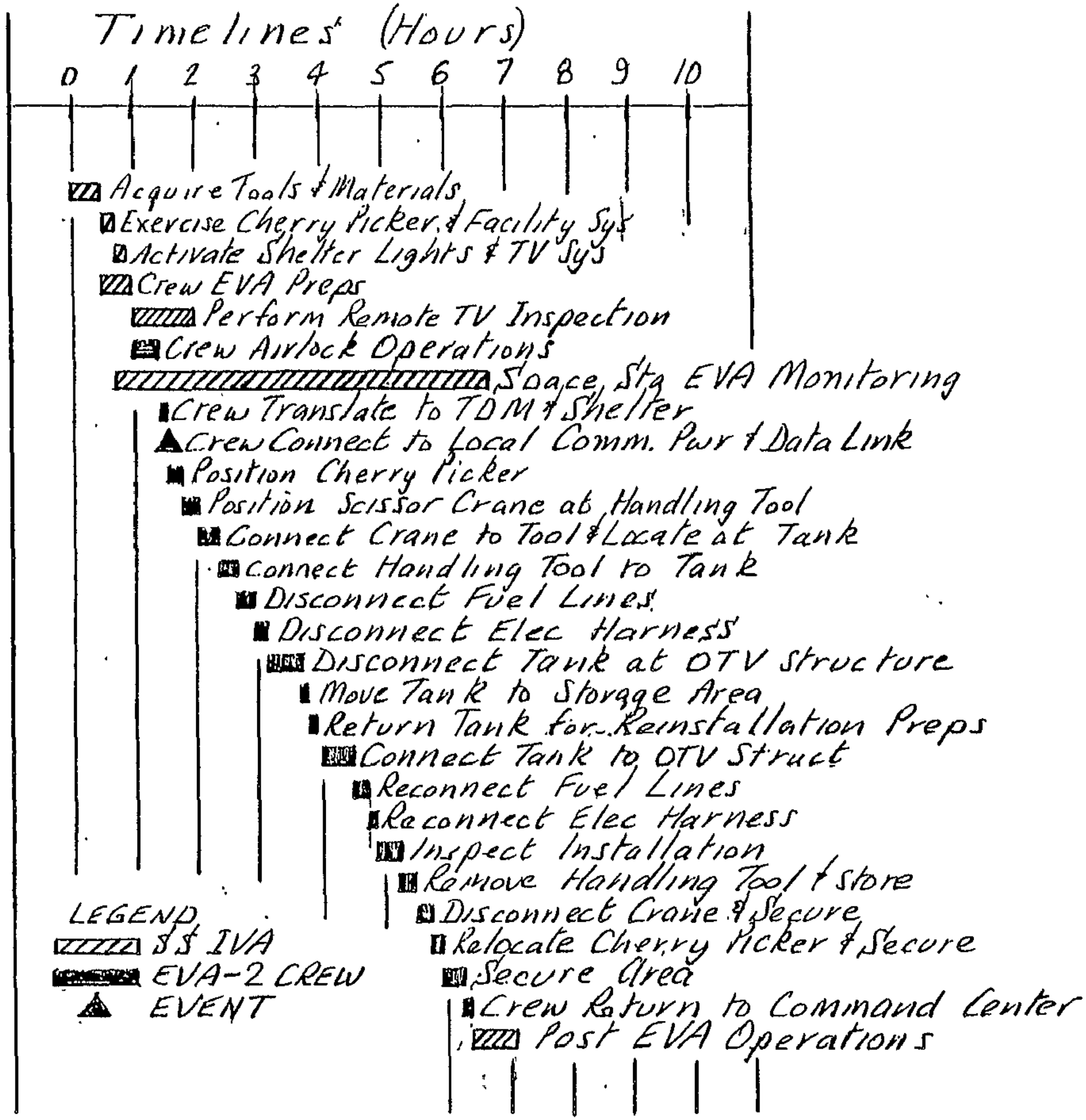


Figure B-17

TDM MAINTENANCE SUMMARY – FUEL TANK CHANGEOUT

FUNCTIONAL REQUIREMENTS	EQUIVALENT GROUND TASK	SPACE STATION TDM TASK	IVA	EVA	SUPPORT EQUIP REQUIREMENTS	COMMENTS
SERVICING. FUEL TANK PREPARATIONS • PREPARE TDM SHELTER/AREA	• VERIFY PWR OFF • INSTALL WORK PLATFORM • EXERCISE SUPP. CRANE	• ACTIVATE SHELTER LIGHTS & TV SYS ON • PLACE SHELTER IN POSITION • EXERCISE CHERRY PICKER • EXERCISE SCISSOR CRANE	✓ ✓ ✓ ✓		CHERRY PICKER DEVICE COMPATIBLE WITH BOTH TDM'S	
• CREW EVA	• ACQUIRE TOOL'S & MATERIALS	• CREW DON EVA SUITS • ACQUIRE TOOLS & MATERIALS			EVA TYPE HAND TOOLS	(1) FUEL TANK WILL BE REMOVED, TRANSLATED TO STORAGE AREA & BE RETURNED FOR REINSTALLATION TO SIMULATE TANK CHANGEOUT OPERATIONS
• REMOTE TV INSPECTION	• PERFORM VISUAL INSPECT • ESTABLISH TASK SCOPE / DESCRIPTION	• PERFORM REMOTE TV INSPECTION. • DETERMINE HEADUP DISPLAY DATA	✓ ✓		REMOTE CONT. TV. SYS ESTABLISH DISPLAY DATA	
• CREW TRANSLATE TO TDM		• COMMAND CENTER COMMENCE EVA MONITOR • CREW EGRESS AIRLOCK & TRANSLATE TO TDM AREA	✓ ✓	✓		(2) MIN ONE FUEL LINE WILL BE SIMULATED
• ESTABLISH COMM, TV AND DATA LINK – COMMAND CENTER/EVA CREW	• ESTABLISH COMM. LINK TO BLOCKHOUSE	• CONNECT EVA CREW TO LOCAL AREA COMM. LINK PANELS	✓	✓	COMM. LINK & PWR SUPPLY PANELS LOCATED THRU TDM & SHELTER AREA	(3) MIN ONE ELEC HARN. WILL BE SIMULATED
SERVICE OPERATIONS: • CHANGEOUT FUEL TANK	• POSITION CRANE • ACQUIRE HANDLING TOOL • CONNECT TOOL TO TANK • DISCONNECT FUEL LINES • PURGE AREA • DISCONNECT ELEC HARNESS • DISCONNECT TANK • MOVE TO STORAGE • CONNECT NEW TANK • CONNECT FUEL LINES • CONNECT. ELEC CABLES • INSPECT	• POSITION SCISSOR CRANE • ACQUIRE HANDLING TOOL • CONNECT TOOL TO TANK (1) • POSITION CHERRY PICKER • DISCONNECT FUEL LINES (2) • DISCONNECT ELEC. HARNESS (3) • DISCONNECT TANK/OTV • MOVE TANK TO STORAGE • RETURN TANK FOR REINSTALLATION PREPS • CONNECT TANK TO OTV. • RECONNECT FUEL LINES • RECONNECT ELEC HARNESS • INSPECT INSTALLATION (4) • DISCONNECT HANDLING TOOL	✓	✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓	SCISSOR TYPE CRANE PART OF SHELTER WITH LOCAL CONTROL DEVICE. TANK HANDLING CRADLE	(4) INSPECT PERFORMED USING BUDDY SYSTEM, EMU HELMET TV AND COMMAND CENTER DATA LINK. (5) HANDLING TOOLS WILL BE STORED ON OR ABOUT THE APPROPRIATE TDM STRUCTURE.
• SECURE AREA	• REMOVE TOOLS & WORK PLATFORMS & SECURE AREA.	• MOVE TOOL TO STORAGE (5) • DISCONNECT CRANE & SECURE • RELOCATE CHERRY PICKER • SECURE AREA & EVA CREW RETURN TO COMMAND CENTER	✓	✓ ✓ ✓ ✓ ✓		

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Figure B-18

AEROBRAKE-SERVICE MAINTENANCE OPERATIONS

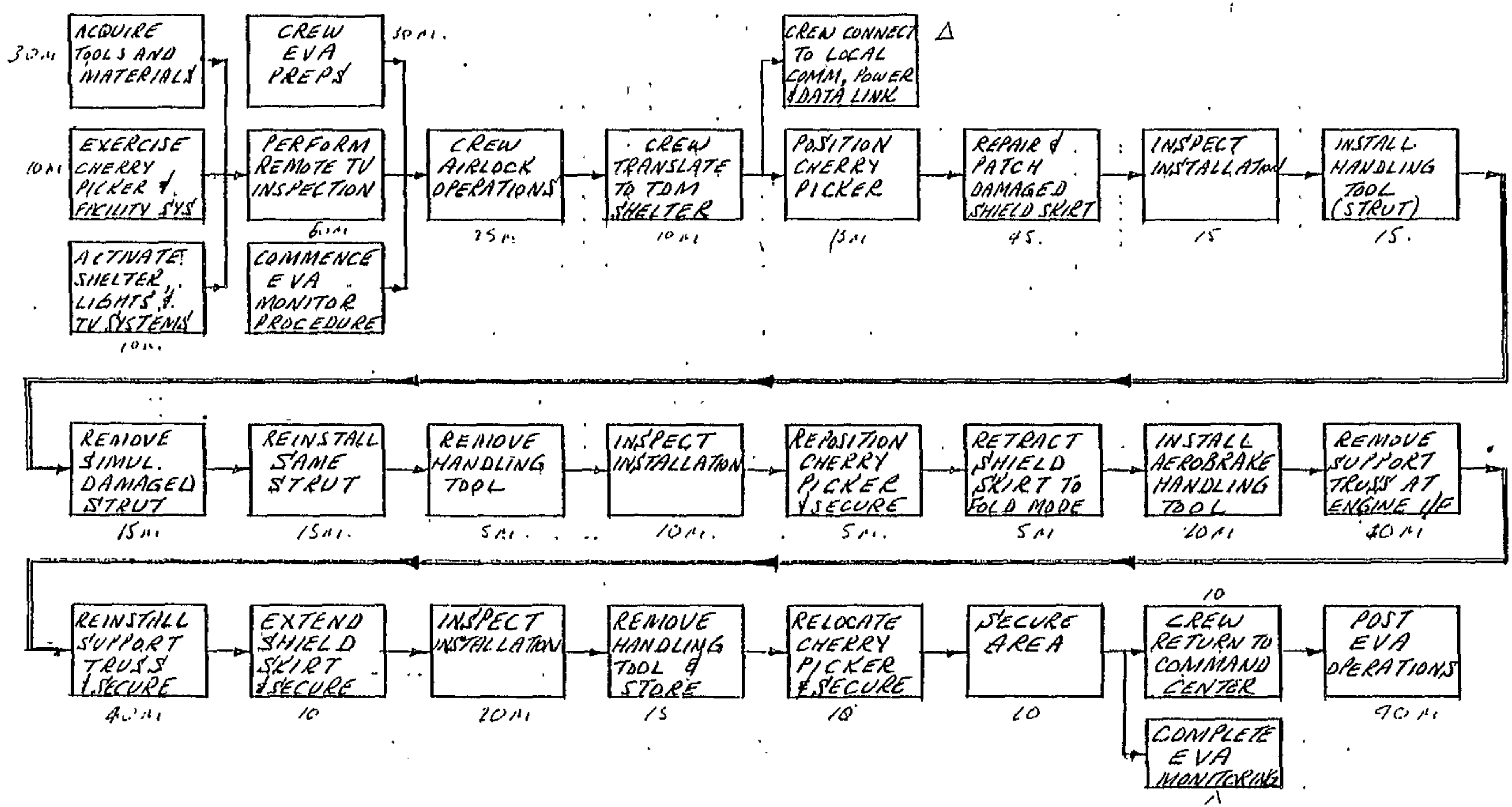

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Figure B-19 AEROBRAKE - SERVICE MAINTENANCE OPERATIONS

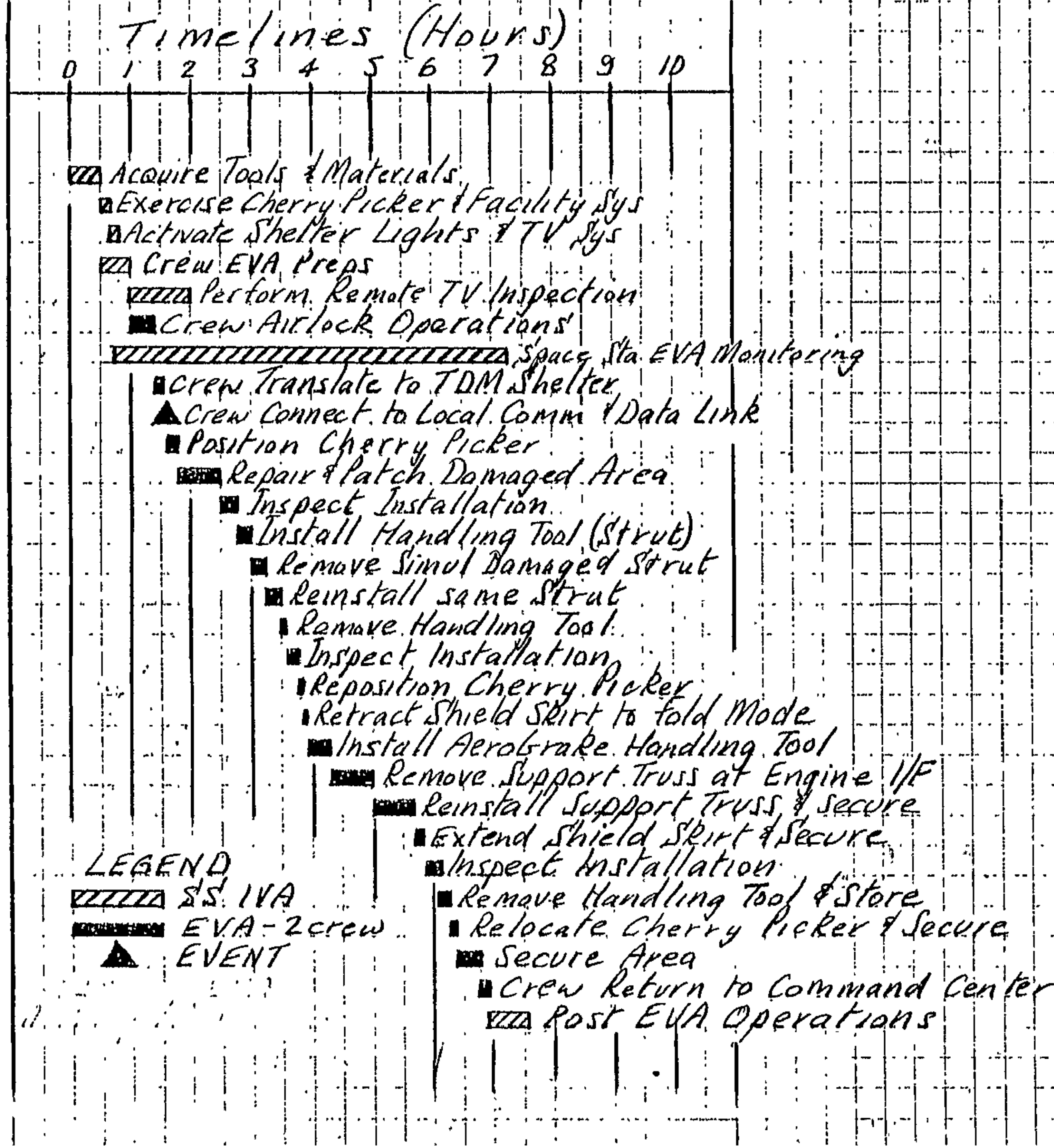

Figure B-20

TDM MAINTENANCE SUMMARY~AEROBRAKE

FUNCTIONAL REQUIREMENTS	EQUIVALENT GROUND TASK	SPACE STATION TDM TASK	IVA	EVA	SUPPORT EQUIP REQUIREMENTS	COMMENTS
SERVICING: AEROBRAKE		• ACTIVATE SHELTER LTS & TV SYSTEM ON	✓			(1) AEROBRAKE FABRIC PATCHING KIT & TYPICAL STRUT REPLACEMENT ARE PROBABLE MATERIALS
PREPARATIONS	• VERIFY PWR OFF	• PLACE SHELTER IN POSITION	✓			
• PREPARE TDM SHELTER/AREA	• INSTALL WORK PLATFORM	• EXERCISE CHERRY PICKER	✓		CHERRY PICKER DEVICE COMPATIBLE WITH BOTH TDM. AREAS	
• CREW EVA	• ACQUIRE TOOLS & MATERIALS	• CREW DON EVA SUITS	✓		EVA TYPE HAND TOOLS	
	• ACQUIRE TASK PLANNING	• ACQUIRE TOOLS & MATERIALS (1)				(2) PERFORMED USING BUDDY SYSTEM, EMU HELMET TV, AND COMM. CENTER DATA LINK. COMBINED.
• REMOTE TV INSPECTION	• PERFORM VISUAL INSPECT	• PERFORM REMOTE TV INSPECTION	✓		REMOTE CONTROL TV	
	• DETERMINE TASK SCOPE DESCRIPTION.	• DETERMINE HEADUP DISPLAY DATA.			ESTABLISH DISPLAY DATA	
• CREW TRANSLATE TO TDM		• COMMAND CENTER COMMENCE EVA. MONITOR.	✓			(3) SELECTED STRUT WILL BE REMOVED AND REPLACED TO SIMULATE REPLACEMENT OPERATION
		• CREW EGRESS AIRLOCK & TRANSLATE TO TDM AREA	✓	✓		
• ESTABLISH COMM, TV AND DATA LINK COMMAND CENTER/EVA CREW	• CONNECT COMM. LINK TO BLOCKHOUSE.	• CONNECT EVA CREW TO LOCAL AREA COMM LINK. PANELS	✓	✓	COMM. LINK & PWR SUPPLY PANELS, LOCATED THRU TDM & SHELTER AREA'S.	
SERVICE OPERATIONS:		• POSITION CHERRY PICKER		✓		
	• LOCATE DAMAGED AREA	• LOCATE DAMAGED AREA		✓		(4) AEROBRAKE SHIELD ASSY WILL BE REMOVED AND REPLACED TO SIMULATE REPLACEMENT OPERATION
• PATCH AND REPAIR SHIELD SKIRT	• REPAIR & PATCH AREA	• REPAIR & PATCH DAMAGE AREA		✓		
	• INSPECT	• INSPECT (2)	✓	✓	HELMET HEADUP DISPLAY	
	• INSTALL HANDLING TOOL	• INSTALL HANDLING TOOL		✓	STRUT REPLACE TOOL	
	• REMOVE STRUT	• REMOVE SIMUL. DAMAGED STRUT (3)		✓		
• REPLACE DAMAGED STRUTS	• INSTALL NEW STRUT					(5) MOST HANDLING TOOLS WILL BE STORED ON OR ABOUT THE APPROPRIATE TDM.
	• MOVE OLD STRUT TO STORE	• REINSTALL SAME STRUT		✓		
	• REMOVE HANDLING TOOL	• REMOVE HANDLING TOOL		✓		
	• INSPECT	• INSPECT INSTALLATION	✓	✓		
	• ACQUIRE NEW AEROBRAKE	• POSITION CHERRY PICKER		✓	LOCAL CONTROL DEVICE FOR CHERRY PICKER	
	• RETRACT SHIELD SKIRT	• RETRACT SHIELD SKIRT TO FOLDED MODE (4)		✓		
• REPLACE AEROBRAKE	• INSTALL HANDLING TOOL	• INSTALL HANDLING TOOL (5)		✓		
	• REMOVE SUPPORT TRUSS	• REMOVE SUPPORT TRUSS		✓		
de Co Co fold mode	• INSTALL NEW AEROBRAKE	• REINSTALL SUPPORT TRUSS		✓		
	• EXTEND SHIELD SKIRT	• EXTEND SHIELD SKIRT		✓		
	• INSPECT INSTALLATION	• INSPECT INSTALLATION	✓	✓		
		• REMOVE HANDLING TOOL & STORE		✓		
• SECURE AREA	• REMOVE TOOLS AND SECURE AREA.	• RELOCATE CHERRY PICKER		✓		
		• SECURE AREA & CREW RETURN TO COMM. CENTER	✓	✓		

Figure B-21

PAYLOAD CHANGEOUT - SERVICE MAINTENANCE OPERATIONS

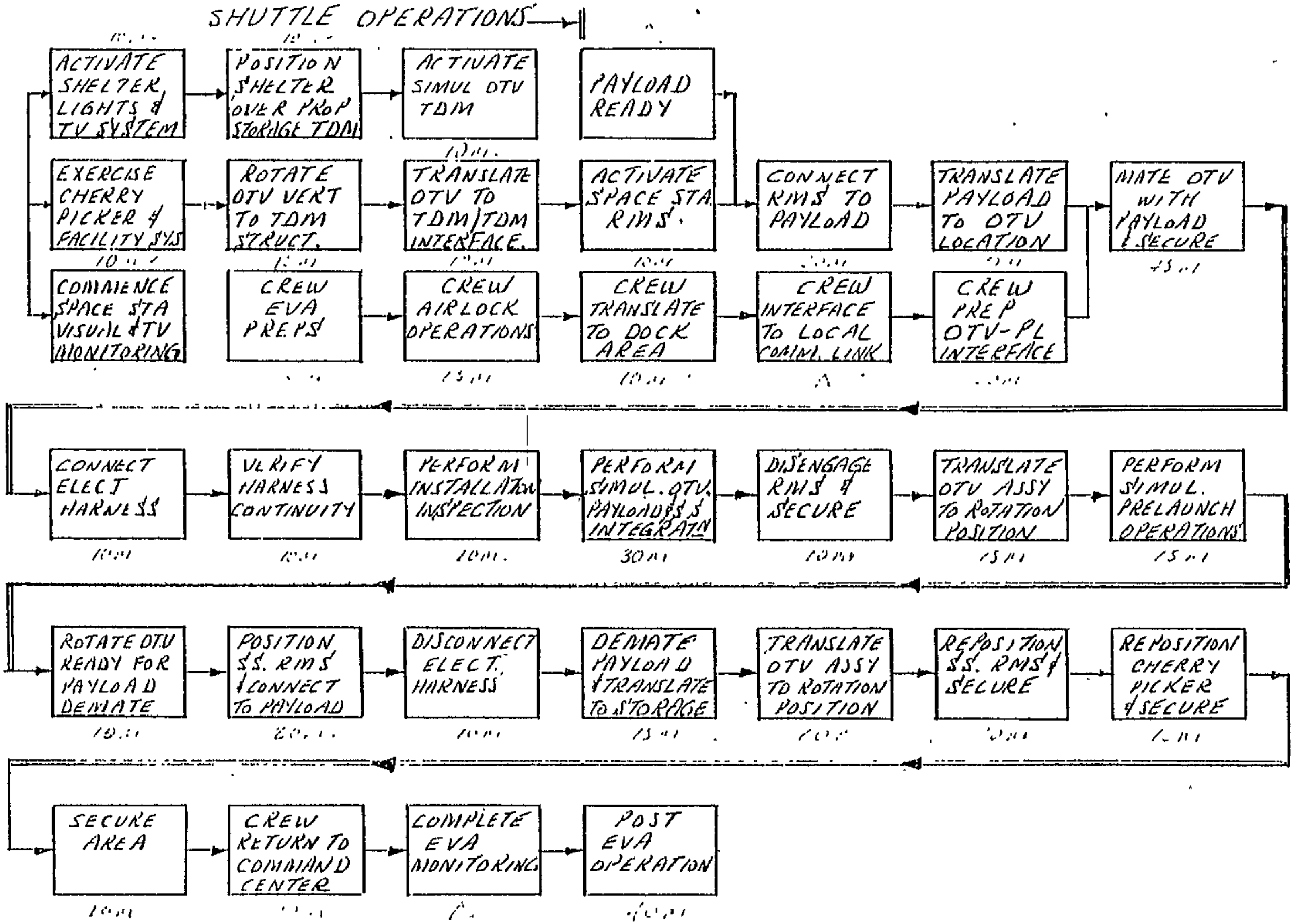

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Figure B-22

PAYLOAD CHANGEOUT- SERVICE MAINTENANCE OPERATIONS

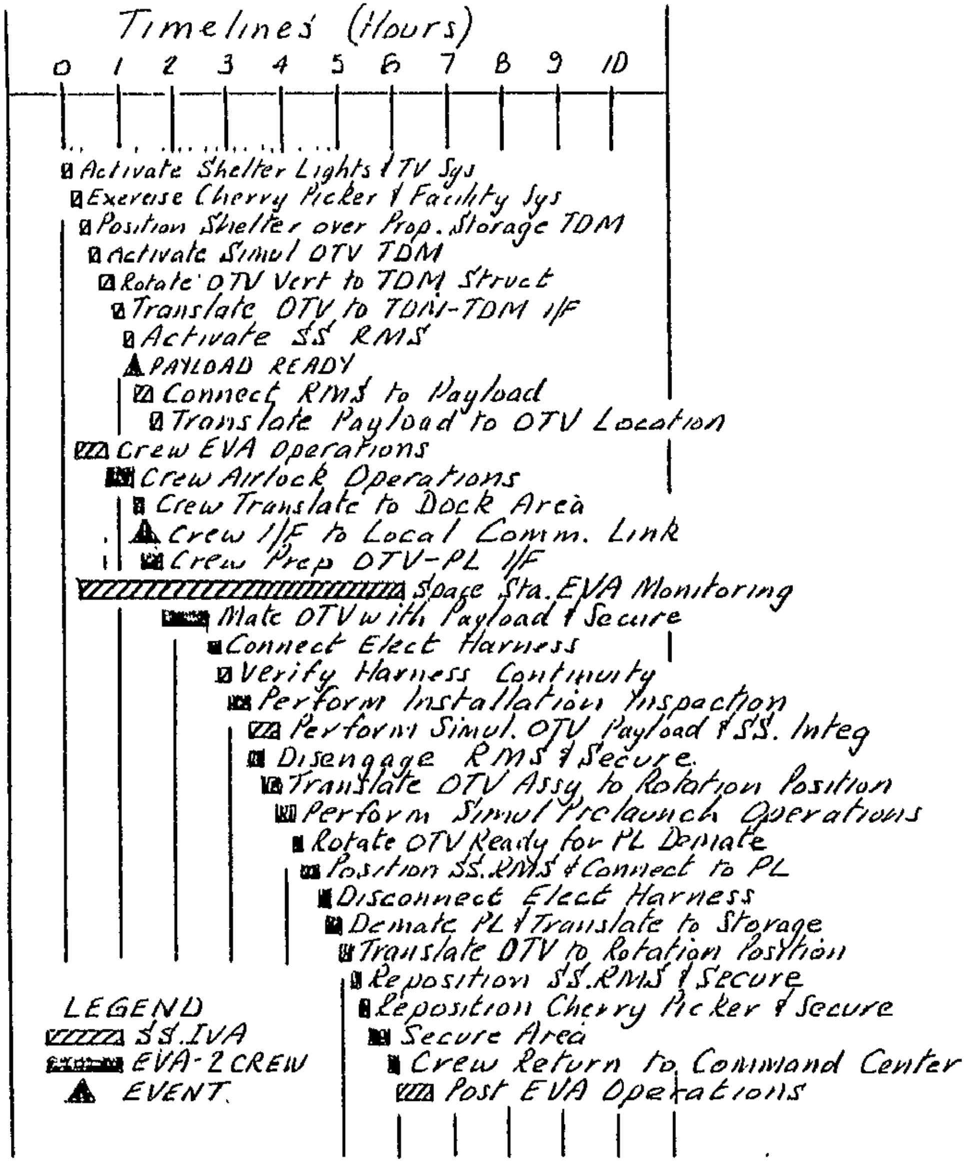

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Figure B-23

PAYLOAD CHANGEOUT – SERVICE & MAINTENANCE OPERATIONS

FUNCTIONAL REQUIREMENTS	EQUIVALENT GROUND TASK	TDM TASK SPACE STATION	IVA	EVA	SUPPORT EQUIP REQUIREMENTS	COMMENTS
SERVICING PAYLOAD PREPARATIONS • PREPARE TDM & SHELTER AREA	• VERIFY POWER OFF • INSTALL WORK PLATFORMS • INSTALL SHELTER	• ACTIVATE SHELTER LTS & TV SYSTEM ON • PLACE SHELTER IN POSITION • EXERCISE CHERRY PICKER	✓ ✓ ✓		CHERRY PICKER DEVICE COMPATIBLE WITH BOTH TDM AREAS	(1) ASSUMES PAYLOAD READY TO BE CONNECTED TO SPACE STATION RMS
• CREW EVA.	• ACQUIRE TOOLS & MATERIALS • ACQUIRE JOB PLANNING	• CREW DON EVA SUITS • ACQUIRE TOOLS/MATERIALS • DETERMINE HEADUP DISPLAY DATA	✓ ✓ ✓		EVA TYPE HAND TOOLS ESTABLISH DISPLAY DATA	
• CREW TRANSLATE TO TDM		• COMMAND CENTER COMMENCE EVA MONITOR • CREW EGRESS AIRLOCK & TRANSLATE TO TDM AREA	✓ ✓	✓		(2) RMS CONNECTION TO PAYLOAD BY SPACE STA. REMOTE CONTROL
• ESTABLISH COMM. TV & DATA LINK BETWEEN COMM CENTER & CREW	• CONNECT COMM. LINK TO BLOCKHOUSE.	• EVA CREW CONNECT TO LOCAL AREA COMM LINK PANELS	✓	✓	COMM. LINK & PWR SUPPLY PANELS LOCATED THRU TDM & SHELTER AREAS	
SERVICE OPERATIONS • RMS & PAYLOAD PREP OPERATION	• PREPARE INTERFACES • CONNECT CRANE TO PAYLOAD & LIFT TO I/F WORK AREA	• ROTATE OTV TO VERTICAL & MOVE TO TDM-TDM I/F LOCATION • ACTIVATE SS RMS & CONNECT TO PAYLOAD (1) • EVA CREW PREP/VERIFY OTV & PAYLOAD INTERFACES	✓ (2)	✓ ✓	SPACE STA. RMS EQUIP' WITH PAYLOAD I/F ADAPTOR	(3) INTEGRATION FUNCTIONS ARE SIMULATED.
• OTV & PAYLOAD MATE OPS	• SAME	• MATE OTV WITH PAYLOAD • CONNECT ELECT HARNESS • VERIFY HARNESS CONTINUITY • PERFORM INSPECTION (4)	✓ ✓	✓ ✓ ✓	HELMET HEADUP DISPLAY	(4) PERFORMED USING BUDDY SYSTEM, EMU HELMET INCORPORATING HEADUP DISPLAY INSPECTION DATA.
• INTEGRATION	• PERFORM CLOSED LOOP TESTS	• INTERGRATE SS.-OTV & PAYLOAD FUNCTIONS (3) • PERFORM SIMUL LAUNCH OPS	✓ ✓			
• DEMATE OTV & PAYLOAD	• SIMILAR	• TRANSLATE OTV INTO POSITION FOR DEMATE OPERATIONS. • DEMATE PAYLOAD & STORE • SECURE RMS		✓ ✓ ✓	PAYLOAD STORAGE AREA IS TBD.	
• SECURE AREA.	• REMOVE TOOLS & WORK PLATFORMS • REMOVE SHELTER • SECURE AREA.	• RELOCATE CHERRY PICKER • SECURE AREA & CREW RETURN TO COMM. AREA	✓	✓ ✓	LOCAL CONTROL DEVICE FOR CHERRY PICKER.	

GENERAL DYNAMICS

Convair Division